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PLASMA-INDUCED COLLECTIVE EFFECTS IN MUON IONIZATION COOLING

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Abstract

Muon ionization cooling is a critical process that determines the achievable beam brightness and overall performance of a muon collider. In this study, we investigate collective effects induced by high-intensity muon beams inside the absorber, effects that have not been included in previous ionization cooling simulations. We show that beam-induced plasma can neutralize the beam space-charge field, while the self-generated azimuthal magnetic field can introduce additional beam focusing through a z-pinch-like mechanism. We also demonstrate that sufficiently high plasma densities may modify the stopping-power rate. The implications of these plasma-induced phenomena for ionization cooling performance are discussed.

INTRODUCTION

Muon ionization cooling is a key process that establishes the achievable beam brightness, including beam intensity and beam size at the interaction point of a muon collider. Ionization cooling occurs when a muon beam traverses an absorber, losing momentum through ionization while external focusing magnets and RF cavities compress the six-dimensional beam phase space. The RF cavities subsequently restore the lost kinetic energy. The overall process is conceptually analogous to a thermodynamic cycle, in which the focused beam in the absorber behaves similarly to an isothermal compression step.

Simulation studies have demonstrated that ionization cooling can reduce the phase-space volume of muon beams by 10^6 without significant decay loss [1]. At the beam densities required for collider operation, collective effects induced by the beam may become significant. These effects have not been explicitly included in previous cooling simulations. In this paper, we analytically examine possible collective phenomena, such as beam-induced plasma formation and associated self-generated magnetic fields, and evaluate how they may modify the beam dynamics within an absorber.

IONIZATION COOLING FORMALISM

Emittance Evolution

The evolution of the normalized emittance can be derived from the derivative of the normalized phase-space volume,

$$\frac{d\varepsilon_n}{ds} = \beta\gamma\frac{d\varepsilon}{ds} + \varepsilon\frac{d\beta\gamma}{ds}. \tag{1}$$

The first term represents emittance growth from stochastic processes (heating), while the second term corresponds to emittance reduction associated with ionization energy loss (cooling). For the transverse normalized emittance, one obtains

$$\frac{d\varepsilon_n}{ds} = \frac{\beta\gamma}{2}\hat{\beta_x}\sigma_\theta^2 - \frac{\varepsilon_n}{\beta^2 E}\left(\frac{dE}{ds}\right), \tag{2}$$

where $\hat{\beta_x}$ is the transverse betatron function and σ_θ is the rms multiple scattering. Equation (2) shows that small $\hat{\beta_x}$, reduced multiple-scattering σ_θ, and a large stopping-power rate (dE/dx) all contribute to achieving lower beam emittance.

Stopping Power Rate

The stopping cross-section can be written as

$$S = \int T(b)d\sigma, \tag{3}$$

where b is the impact parameter, $T(b)$ is the energy transferred in a collision at b, and $d\sigma$ is the differential cross-section. For Coulomb scattering, the differential cross-section in terms of b is

$$\begin{aligned} d\sigma &= 2\pi b \cdot db \\ &\sim 2\pi\frac{e_1^2 e_2^2}{m_2 v^2}\frac{dT}{T^2}, \end{aligned} \tag{4}$$

where e_1 and e_2 are the charges of the incident and target particles, m_2 is the target mass, and v is the velocity of the incident particle. Integrating over the allowed range of energy transfer gives

$$S = 4\pi\frac{e_1^2 e_2^2}{m_2 v^2}\left[\frac{1}{2}\ln(T^2)\right]_{T_{min}}^{T_{max}}, \tag{5}$$

where T_{max} and T_{min} correspond to the maximum and minimum energy transfer. T_{max} represents a head-on collision with a target electron, while T_{min} reflects the mean excitation energy of atomic electrons of the target particle. The logarithmic term is known as the Coulomb logarithm.

The stopping-power rate is then

$$\left\langle -\frac{dE}{dx}\right\rangle = S \cdot N, \tag{6}$$

where N is the number density of the absorber. Including relativistic and quantum corrections yields the Bethe stopping-power formula. For muon ionization cooling, the typical muon momentum is around 200 MeV/c, and the stopping-power rate becomes

$$\left\langle -\frac{dE}{dx}\right\rangle = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I^2}W_{max}\right) - \beta^2\right], \tag{7}$$

where $K = 0.307075$ MeV mol^{-1} cm^2, Z and A are atomic number and mass of the absorber, z is the charge number of

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DEVELOPMENT OF AN ELECTRON COOLER FOR THE HIAF ACCELERATOR*

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Abstract

The High Intensity heavy-ion Accelerator Facility (HIAF) is a mega scientific infrastructure in China. It consists of a superconducting electron cyclotron resonance ion source (SECR), a superconducting heavy ion linac (iLinac), a fast-ramping rate synchrotron (BRing) and six experimental terminals. One major task is to study atomic physics with internal targets in the spectrometer ring (SRing). An electron cooler was designed and constructed in SRing to boost the internal target experimental luminosities and compensate for energy losses. In this paper, the current status of the cooler was presented.

INTRODUCTION

HIAF is a new accelerator complex hosted by the Institute of Modern Physics (IMP) Chinese Academy of Sciences (CAS) [1]. It is designed to provide intense primary heavy ion beams and produce rare secondary isotopes for nuclear physics, atomic physics and application sciences. The project was proposed in 2011 and approved in 2015. The construction began in 2018 and the first beam commissioning was completed successfully on October 28th, 2025. An aerial view of the HIAF campus is shown in Figure 1.

Figure 1: Aerial view of the HIAF project campus.

SRing is one the of six terminals in the HIAF project. It was designed with different operation modes. The isochronous mass spectrometer (IMS) mode is used to measure short-lived nucleus mass. The internal target mode is used for experiments on the gas target and the electron target. The normal mode is used for ion/isotope accumulation. The electron cooling method is used to improve luminosities for the last two modes.

The HIAF accelerator layout is shown in Figure 2. A typical operation mode can be described as following. Ions provided by SECR and iLinac are accumulated and accelerated in BRing, then be extracted and transferred in HFRS. Secondary beam (highly charged ions or isotopes) can be produced by bombarding a target with the primary beam. The secondary beams (isotopes or highly charged heavy ions) will be injected into SRing and stored for experiments. In the future, a deceleration cavity will be used to prepare low-energy highly-charged ions for atomic physics.

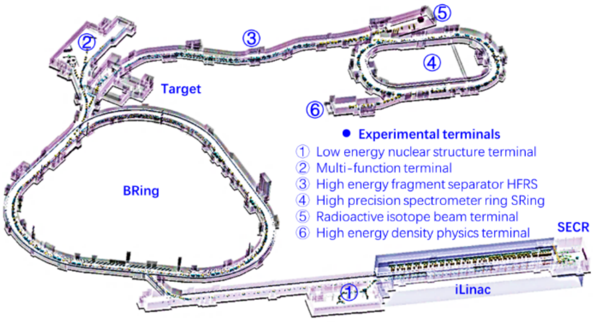

Figure 2: HIAF accelerator layout.

The electron cooler in SRing is a classical magnetized DC cooler [2]. The maximum electron energy and current are 450 keV and 2.0 A, respectively. The cooler was designed based on the existing cooler installed in HIRFL-CSRe at IMP, which was made by collaboration with BINP in 2004. The total cooler assembling was finished in May of 2025. A primary commissioning with few hundreds milliamperes electron beam at 200 keV was achieved successfully. A photo of the cooler assembled in the tunnel is shown in Figure 3.

Figure 3: HIAF electron cooler.

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RESEARCH AND DEVELOPMENT OF AN ULTRAHIGH-PRECISION SINGLE-ION IMPLANTER

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Abstract

Ion implantation is an accelerator-based technology used to create defects and introducing impurities into solid materials. A research and development study is currently underway toward ultrahigh-precision single-ion implantation using laser-cooling techniques at Takasaki Institute, National Institutes for Quantum Science and Technology. To achieve this, we incorporate a linear Paul trap as an ultracold single-ion source, where trapped ions can be made “Coulomb-crystallized” through Doppler laser cooling. In our scheme, nitrogen or silicon ions, useful for ion implantation to create color centers in materials, are sympathetically cooled through Coulomb collisions by co-trapping them with laser-cooled calcium ions to form a two-component crystal. These cold ions are then selectively extracted from the trap to be accelerated and focused through a 50-kV electrostatic bipotential-lens system. Our goal is to achieve beam focusing for ultrahigh-precision implantation on the order of 10 nm. The implanter system has already been assembled, and the commissioning is currently ongoing to enable single-ion extraction using a Coulomb crystal. In these proceedings, we describe the scheme for selective ion extraction and nanobeam focusing based on multiparticle simulations and briefly report recent progress in system implementation.

INTRODUCTION

Improving the focusing and targeting precision of charged-particle beams is an important aspect of accelerator technology. One example is so-called “microbeam (nanobeam) irradiation”, where the transverse spot size of the beam on a target is focused to the micrometer (nanometer) scale. This technique is often employed for pinpoint irradiation in MV-class electrostatic accelerators [1]. In this beam-irradiation method, the beam generated from such a high-energy accelerator is strongly collimated to reduce its effective emittance before final focusing on the target. (Note that this process is not beam cooling as the phase-space density of the beam is not increased.) With fine tuning of the collimator apertures and stronger final focusing, the spot size can, in principle, be further reduced. However, it would be practically more difficult to control single-ion irradiation reliably because of the stochastic nature of ion transmission through collimators in conventional beam-formation methods.

A different approach to obtaining low-emittance beams is beam cooling. Among several cooling methods applicable to fast heavy-ion beams, Doppler laser cooling is the most promising since the lowest attainable temperature is in the mK range [2, 3]. In such an ultralow-temperature state, it is expected that a crystalline-ordered beam, whose emittance is extremely low, can be formed [4, 5]. Although the longitudinal beam temperature of around 1 mK was attained in early laser-cooling experiments [6], transverse cooling to the mK range has not yet been realized (except in very low-beam-energy cases using a circular Paul trap [7]). This is mainly because it is practically quite difficult to maintain high lattice periodicity for avoiding resonance crossing, to accomplish three-dimensional laser cooling, and to compensate for dispersive effects in large-scale storage rings [8].

As a possible method to generate a three-dimensionally ultralow-emittance beam and control single-ion motion reliably, we consider the use of a linear Paul trap (LPT) for several following prominent reasons. It is relatively straightforward to form an ion Coulomb crystal, an ordered state in au ultralow-temperature limit, by applying Doppler cooling to trapped ions [9]. Attainable normalized emittance is on the order of 10^{-15} m·rad or less [10-12]. It is possible to observe the existence of a small number of ions in a crystal and to manipulate them individually under wide-range operating conditions for extraction from the LPT [11-14]. Furthermore, two-component crystals can be formed via sympathetic cooling of various ions co-trapped with laser-coolable ions.

Recently, we have proposed an ultrahigh-precision single-ion implanter for the application of quantum technology [15, 16]. In the following, we present the scheme of single-ion irradiation and nanobeam formation using a Coulomb crystal and report on the progress of ion-trap experiment performed at QST Takasaki Institute.

SINGLE-ION IMPLANTER

We have fabricated a compact ion-implanter system with an LPT at QST Takasaki Institute. As shown in Fig. 1, it mainly consists of an external ion source where various implantation ions (such as N and Si) can be generated, an LPT where a two-component Coulomb crystal is formed by laser cooling of Ca^+ ions (Doppler limit: 0.5 mK) and single-

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HADRON BEAM COOLING CONCEPT AND COOLER DESIGN STATUS FOR THE EIC *

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Abstract

Cooling of hadrons in Electron Ion Collider (EIC) is critical to achieve EIC design parameters and performance. In this paper we summarize current strategy of hadron beam cooling application for the EIC starting with providing strong cooling of proton beam emittances at injection energy and potential subsequent cooling at the top collision energies. We will then discuss requirements, challenges and design status of RF-based electron cooler for 23.8 GeV proton energy.

INTRODUCTION

The Electron-Ion Collider (EIC) project is presently under design at Brookhaven National Laboratory (BNL); a layout of the EIC is shown in Fig. 1. Collisions occur between the hadrons in the Hadron Storage Ring (HSR) and the electrons in the Electron Storage Ring (ESR) [1].

In order to achieve the design emittances of the hadron beam, hadron beams will be injected into the HSR and cooled to the target emittances at injection energy of protons of 23.8 GeV. After the target emittances are achieved, the HSR will be ramped to the collision energy.

Cooling of protons at 23.8 GeV will be done using conventional electron cooling technique which requires 12.5 MeV electron accelerator. The design of such Low-Energy Cooler (LEC) is based on the RF-accelerated electron bunches, similar to the LEReC [2] approach, but scaled to higher energy.

Cooling of heavy ions at collision energies is planned using stochastic cooling technique [3].

Presently, no cooling of protons at collision energies is implemented. However, such high-energy cooling of protons can be considered as future EIC upgrade.

HIGH-ENERGY COOLING

A robust cooling of protons at collision energies in the EIC could significantly increase luminosity in the EIC. However, designing of such High-Energy Cooling (HEC) system for protons is one the most challenging problems in modern accelerator physics.

Recently, significant efforts were devoted to design of such HEC system using stochastic cooling approach but employing electron beam itself as a pick-up, amplifier and kicker, which can extend this technique to much higher bandwidth than possible with conventional microwave technology. A conceptual design study of such an approach based on the micro-bunched Coherent Electron Cooling amplifier was performed [4].

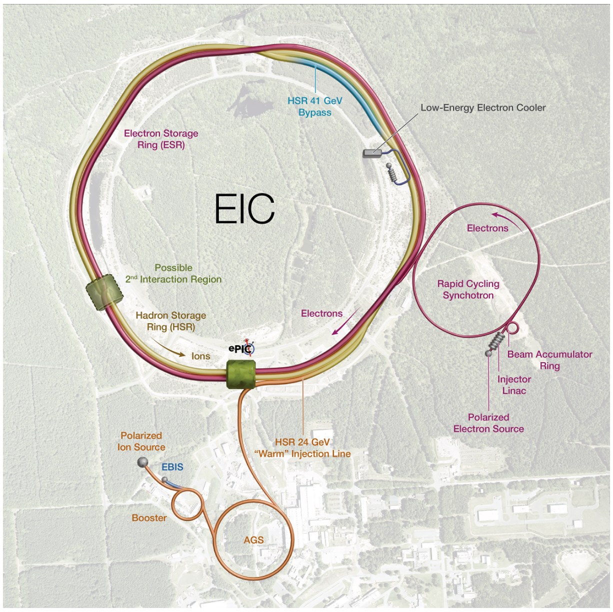

Figure 1: The layout of the Electron-Ion Collider (EIC).

One of the alternative approaches is to use a well-established technique of electron cooling. With such a technique, the cooling rate drops quadratically with energy which makes its extension to high energies challenging. However, the drop of cooling rate with energy can be compensated by an increase in the phase-space density of electron bunches, length of the cooling section and by precooling of hadron beam at lower energies, as cooling rate strongly depends on the divergence of the hadron beam.

Since electron cooling technique has several decades of experience one can provide estimates of the cooling rates and requirements of needed electron beam parameters with very high degree of certainty. What remains is to design required electron accelerator.

Several approaches using conventional electron cooling for the HEC system were considered in the past [5-8]. Most recent R&D studies at BNL were devoted to two approaches: 1) Storage Ring-based Electron Cooler [9] and 2) ERL-based Electron Cooler [10].

While R&D on the HEC continues, immediate focus for the EIC is on the design of the Low-Energy Cooler (LEC).

THE LEC REQUIREMENTS

The LEC design is based on the non-magnetized cooling approach with zero magnetic field on the cathode and no magnetic field in the cooling region [11]. The layout of the LEC accelerator is shown in Fig. 2.

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ELECTRON ION COLLIDER STRONG HADRON COOLING DESIGN SUMMARY

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Abstract

The Electron-Ion Collider (EIC) requires a high-energy cooler to maintain excellent beam quality and achieve high luminosity throughout long collision stores. To meet this requirement, the EIC project has adopted a novel approach known as Coherent Electron Cooling (CeC)—referred to as Strong Hadron Cooling (SHC)—which can provide rapid cooling rates at high energies. The SHC relies on an Energy Recovery Linac (ERL) to provide the intense, high-quality, and low-noise electron beam essential for the cooling process. This talk will overview and summarize the design progress of the Strong Hadron Cooler for the EIC. We will discuss key aspects of the project, including cooling physics, main parameters, the ERL design, risk mitigation strategies, and remaining challenges. Successful outcomes in foundational R&Ds could pave the way for a future proposal to implement SHC as an upgrade to the EIC, unlocking its full luminosity potential.

INTRODUCTION

Hadron Beam cooling is essential for substantially reducing the emittance of the proton or ion beams and preserving these parameters throughout the beam store in the EIC to maintain the average luminosity nearly equal to its peak value of $1.03 \times 10^{34}\ \mathrm{s^{-1}\,cm^{-2}}$ for e-p collisions at a center-of-mass energy (E_{cm}) of 105 GeV.

Due to high particle densities, conventional stochastic cooling systems for the EIC's proton beams require a 10- to 100-fold increase in bandwidth to provide the cooling rates needed to suppress IBS-induced emittance growth and the corresponding luminosity reduction.

Two primary hadron cooling systems are planned for the EIC: a Low-Energy Cooler (LEC) for hadrons at the injection energy of 24.5 GeV, and a high-energy cooler to maintain luminosity at collision energies of 100 GeV and 275 GeV. The latter is the main Strong Hadron Cooling (SHC) system for the project [1, 2]. This report, follows more detailed design report [3], summarizes the design progress of the SHC.

EIC HIGH ENERGY COOLING REQUIREMENTS AND ROADMAP

The EIC SHC is essential for the EIC to achieve a luminosity of $1 \times 10^{34}\ \mathrm{cm^{-2}\,s^{-1}}$. The key cooling requirements are:

- Counteract longitudinal and transverse emittance growth during long stores. The cooling time must be less than or equal to the emittance growth time from all diffusion sources. The dominant source is Intra-Beam Scattering (IBS), with longitudinal and horizontal growth times of 2 h to 3 h. The beam-beam diffusion time is approximately 5 h in the vertical plane.
- Provide cooling at top energies (275 GeV for protons, as well as 100 GeV and 41 GeV).
- Ensure the cooling section hardware fits within the available space in the IR-2 tunnel.
- Accommodate various ion species, including protons, ^{3}He, and heavy ions up to gold.

Following a 2020 review, CeC was selected as the primary method for the EIC's high-energy cooler, referred to as SHC in the EIC.

During the 2023 design phase, it became clear that a conventional electron cooler was a desirable addition at the injection energy. This cooler would be integrated into the same ERL to achieve the required beam emittances at lower energies (e.g., the 24 GeV injection energy) and provide a potential path for a 41 GeV storage cooler. Consequently, the EIC hadron cooler scope was updated to include both an SHC and a low energy conventional electron cooler (LEC).

By 2025, significant technical risks associated with the high-energy cooling system remained unresolved, and luminosity studies indicated that even with the SHC scenario, the projected average luminosity would be less than half of the ultimate requirement [4]. Consequently, due to these unresolved risks and performance limitations, the design efforts for advanced high-energy cooling—including both SHC and the storage ring cooler designs, were terminated within the EIC project scope. The mitigation of remaining risks is now being pursued by resources outside of the main project.

STRONG HADRON COOLING DESIGN

The design study for microbunched electron cooling includes the following activities:

- **Cooling Physics Modeling:** Develop and apply physics models and simulation codes to represent the cooling process accurately.
- **Cooling Section Design:** Engineer the lattice, magnets, and diagnostic systems for the complete cooling section.

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EIC LUMINOSITY MODELS FOR VARIOUS HADRON COOLING SCENARIOS*

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Abstract

We have developed a simulation to model the evolution of proton and heavy-ion bunches stored in the Electron-Ion Collider's Hadron Storage Ring (HSR) over the course of several hours, taking into account intrabeam scattering, the beambeam effect, and particle loss. This has enabled us to predict how various cooling schemes, including microbunched electron cooling and microwave stochastic cooling, would impact the collider's luminosity. We discuss the details of this code and show the luminosity evolution for various scenarios.

INTRODUCTION

The Electron-Ion Collider (EIC) is a new collider which will be built at Brookhaven National Laboratory to probe nuclear structure through the collision of electrons with various ion species. In order to improve luminosity, various cooling scenarios are considered, including a low-energy cooler to create initial flat hadron beams [1] as well as stochastic and microbunched electron cooling at store to maintain the beam emittance [2, 3]. Since not all of these systems may be available at startup, it is desirable to have a simulation code which will enable us to quantify the performance of the various cooling systems and operational modes.

To achieve this goal, we have developed a long-term luminosity model. This evolves a bunch of hadrons[1] over the course of the several-hour store and uses this information to compute changes in the luminosity. We discuss the details of this model and the various physical effects included, then show luminosity evolution for various physics cases.

MODEL DETAILS

Our model is an extension of the long-term tracking developed for studies of microbunched electron cooling [3]. We initialize a bunch of hadron macroparticles and then use a small number of transfer matrices to transport them between a handful of key locations in the EIC's hadron storage ring (HSR), allowing the macroparticles to sample their full phase space. We include both 591 and 197 MHz RF cavities to provide sinusoidal energy kicks to the hadrons each turn. We manually add in the interesting dynamic effects, including intrabeam and Touschek scattering, the beambeam effect, and cooling, as will be described in the subsequent subsections. In order to simulate many real turns in a small number of simulated turns, we let each simulated turn represent $N >> 1$ real turns by increasing coherent cooling kicks by a factor N and incoherent kicks by $\sqrt{N}$.

Intrabeam Scattering (IBS)

We calculate intrabeam scattering rates using the formulas in [5]. These are equivalent to the usual Bjorken-Mtingwa formalism [6], but written in terms of elliptic integrals which can be quickly evaluated using the methods of [7]. Due to our explicit implementation of large-amplitude Touschek kicks, as will be discussed later, we restrict the maximum momentum kick in the Coulomb logarithm to be the minimum momentum kick we use for our calculations of Touschek scattering.

As inputs to the IBS calculation, we require the optics around the ring as well as information about the bunch distribution. The optics are simply sampled at 1000 equidistant points of the HSR, with coarser sampling not giving any advantage. The beam transverse emittances are calculated by fitting the distributions of the particles' transverse actions to exponentials, and the bunch length and energy spread are found by fitting the distributions of longitudinal position and energy offset to Gaussians, with the longitudinal bunch positions further constrained to lie within the central 591 MHz RF bucket. This allows us to focus our studies on the core of the beam as opposed to the potentially large tails.

Once the IBS rates are calculated, we apply Gaussian random kicks to each macroparticle in each of the 3 planes in a zero-dispersion location. These kicks have mean 0 and standard deviation chosen to produce the correct heating rates. Additionally, the sizes of the kicks to a given macroparticle are scaled by the square root of the hadron's local density relative to the average density in the 591 MHz RF bucket, since we expect that the heating rate for an individual particle will increase as it moves toward the core of the bunch.

Beambeam Effect

The beambeam effect results in an emittance growth in the hadron beam due to the strong nonlinear force exerted by the electrons. Since this is a complex phenomenon, we simply assume a constant beambeam growth time of 20 hours horizontally and 5 hours vertically for protons and no beambeam growth for heavy ions due to their smaller beambeam parameter [4]. The implementation of the kicks is the same as described for IBS in the previous subsection, except that we do not perform the density scaling, since this is not expected to be the case for beambeam.

Touschek Scattering

While IBS models the emittance growth due to many small-angle scattering events, there is also a non-zero probability that a given hadron will receive a single large energy

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[1] We do not need to do anything special for the electron beam, since its emittance is held constant by radiation damping and the bunches are frequently replaced for polarization reasons [4].

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DEVELOPMENT OF STORAGE RING ELECTRON COOLER FOR HIGH ENERGY APPLICATIONS *

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Abstract

Electron cooling at high energy requires large average current in the cooling section (CS), which can be achieved by reusing the same electron beam on many passes through the CS. One of the options to realize such a cooling scheme is to use an electron storage ring with electrons being cooled by dedicated radiation damping wigglers. We will discuss the conceptual design of the 150 MeV Ring Electron Cooler as a potential future application for the Electron Ion Collider.

INTRODUCTION

Cooling of protons in the Electron Ion Collider (EIC) [1] at top energy ($\gamma = 293$) to counteract the IBS-driven emittance growth will be needed to achieve the design average luminosity at EIC. Electron Cooling [2] can provide such a capability.

Extending electron cooling to the high energies requires substantial electron current in the cooling section. To relax requirements to an injector, one can reuse the same electron beam on multiple turns. In this paper we consider a multi-turn electron cooling based on the Ring Electron Cooler.

In REC, electron bunches are stored in a dedicated storage ring, and the same e-bunches are reused for the cooling on multiple turns. The electrons' emittances are preserved during the storage cycle by counteracting heating caused by various scattering mechanisms with radiation damping facilitated by dedicated damping wigglers.

The REC utilizes a non-magnetized RF-based electron cooling, which was successfully applied at LEReC [3-6] during RHIC operation in 2019-2021 runs.

RING ELECTRON COOLER

The Ring Electron Cooler must be compatible with the EIC Low Energy Cooler (LEC) [7] and must share the cooling section with the LEC.

While the LEC "precools" the protons at the injection energy to the design emittances (Table 2), the REC's preserves the emittances at the collision energy by providing horizontal and longitudinal cooling times of 2 and 3 hours respectively.

REC Layout and Lattice

The REC layout is shown in Fig. 1. The REC lattice is shown in Fig. 2.

The electron storage ring is a trapezoidal shape "racetrack" with the CS and damping wigglers occupy most it.

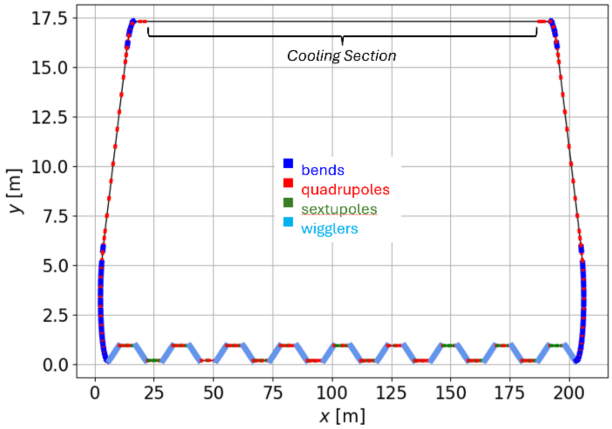

Figure 1: The Ring Electron Cooler layout.

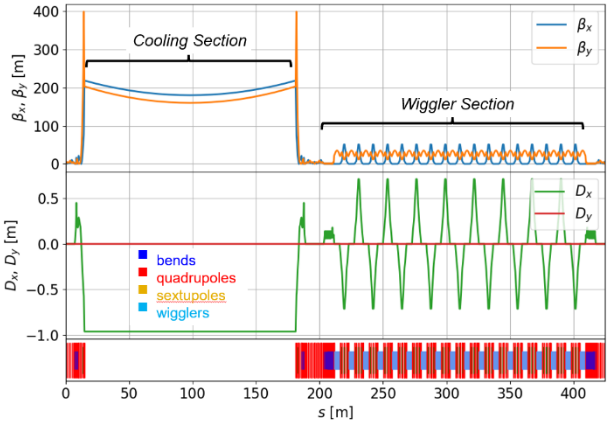

Figure 2: The Ring Electron Cooler lattice.

The cooling section is 170 m long. It is shielded by several layers of μ-metal, which provides at least factor of 1000 attenuation of ambient magnetic fields. The BPMs and trajectory correctors are located every 12 m in the CS.

About one meter of electron dispersion in the cooling section is needed to provide the required cooling times.

A wiggler section is opposite to the cooling section. It contains 18 damping wigglers. The wigglers must provide enough radiation cooling of the electron bunches to counteract the effects of the electrons intra-beam scattering (IBS) and beam-beam scattering (BBS) of electrons on protons in the CS.

The arcs connecting the wiggler section and the CS contain 10 m long straight sections with adjustable optics suitable for placement of injection and RF systems.

REC Parameters

The REC parameters are listed in Tables 1 and 2.

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UV LASER SYSTEMS FOR COOLING RELATIVISTIC BUNCHED ION BEAMS AT THE SIS100

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Abstract

In this contribution, we present two high power ultraviolet (UV) laser systems and their integration for laser cooling at the heavy ion synchrotron SIS100 at FAIR (Facility for Antiproton and Ion Research).

The tunable continuous wave (cw) laser system operates at 257 nm, generated through two consecutive stages of second-harmonic generation (SHG), is optimized for long-term stability and high UV output power. Employing elliptical focusing in the second enhancement cavity, an output power exceeding 2.8 W in the UV could be demonstrated. Stable long-term UV generation is achieved at 2 W, ensuring reliable operation for extended experimental runs.

The pulsed laser system, also based on two frequency conversion stages, delivers more than 5 W of UV output power at 257 nm with a tunable frequency range exceeding 3 THz. The duration of the pulses is adjustable between 46–734 ps with repetition rates of 1–10 MHz, enabling synchronization with ion bunches.

Overall, we anticipate the use of three laser systems; the two detailed here as well as a second pulsed laser provided by the University of Dresden group. We present a scheme for precise spatial, temporal and energetic overlap of the three laser systems with the bunched ion beams.

INTRODUCTION

Laser cooling is a promising technique for achieving narrow longitudinal momentum distributions in relativistic, bunched ion beams, which is essential for high-precision experiments at modern accelerator facilities such as the heavy ion synchrotron SIS100 at FAIR. For the SIS100, laser cooling is the only intended beam cooling method.

In theory, relative longitudinal momentum spreads of $\Delta p/p = 10^{-7}$ can be achieved [1]. Laser cooling has been successfully demonstrated at the Experimental Storage Ring (ESR) at GSI using both continuous wave (cw) and pulsed laser systems individually [2, 3]. For fast and efficient cooling, three laser systems will be operated simultaneously [4]. The two pulsed lasers, with spectral widths of several hundred GHz, will cover a broad range of ion velocities. The cw laser, with an instantaneous linewidth of less than 1 MHz, will cool the ions near their ideal velocity [5].

Reliable operation of these systems requires broad tunability of the laser frequencies as well as high and stable output powers in the green (514 nm) and UV (257 nm), as both wavelengths can be used for laser cooling at the SIS100 [5].

CONTINUOUS WAVE LASER SYSTEM

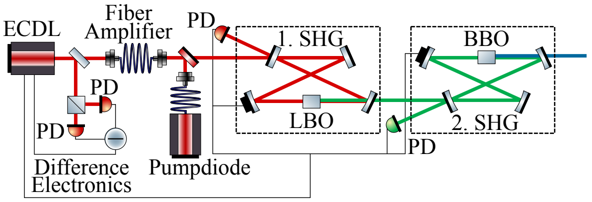

Figure 1: Simplified setup of the cw laser system.

The cw laser system (cf. Fig. 1) consists of an external cavity diode laser (ECDL) emitting a fundamental wavelength of 1028 nm. To avoid mode hops of the ECDL, a polarization based locking scheme adapting the current is implemented [6]. The infrared (IR) light is amplified in an ytterbium doped fiber amplifier up to 37 W, which is only limited by the fiber damage threshold.

Frequency conversion is employed to convert the IR light into the green and then the UV spectral range. The first second-harmonic generation (SHG) is realized in a spherical enhancement cavity in a bow-tie configuration employing a 15 mm long lithium triborate (LBO) crystal non-critically phase-matched by temperature. With up to 95 % mode-matching efficiency and a Pound-Drever-Hall (PDH) locking scheme [7] implemented using the open source software PyRPL [8], an output power of 25.2(6) W at 514 nm is achieved with conversion efficiencies up to 70 %. To ensure reliable operation, an automated relocking system is embedded.

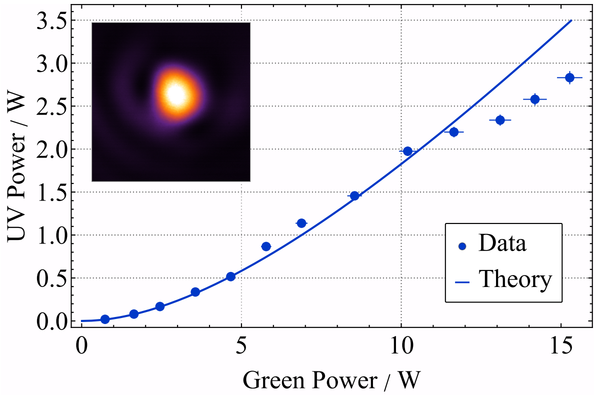

Figure 2: UV output power of the elliptical focusing enhancement cavity against the power of the fundamental green light. The dots mark the measured data, the line the corresponding theory according to Steinbach et al. [9]. The inset shows the corresponding beam profile at 2 W in the UV.

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SCHOTTKY SPECTRA OF LASER-COOLED BUNCHED ION BEAMS: SIMULATIONS AND RECENT EXPERIMENTAL RESULTS FROM THE CSRe*

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Abstract

Schottky spectra of longitudinal bunched ion beams are not as well studied as those of coasting ion beams. Much less is known about what they actually exhibit and how this should be interpreted. At the storage ring CSRe, we have systematically studied the longitudinal dynamics of O^{5+} ion beams by means of Schottky analysis. Besides, a multi-particle tracking code using a differential equation model has been developed to simulate the longitudinal Schottky spectra of bunched ion beams. Based on the experimental and simulation results, we propose a novel method to extract the longitudinal momentum distribution from the Schottky spectra of the bunched ion beams. In addition, we have systematically investigated the Schottky spectra of bunched Kr^{30+} ion beams both experimentally and by simulations, and provide a detailed interpretation of the extremely strong central peak caused by the coherent effect.

INTRODUCTION

In storage rings, longitudinal bunched ion beams are produced by applying a sinusoidal voltage through an RF-buncher, which longitudinally modulates the coasting ion beams. This bunching process is essential for manipulating the longitudinal properties of ion beams, such as accelerating or decelerating beam energy, reducing their longitudinal spatial size, and achieving higher spatial density and luminosity [1]. Nowadays, bunched ion beams have been widely used for experiments at storage rings, such as precision laser spectroscopy experiments [2, 3] and collision experiments [4, 5].

In these experiments, a Schottky detector plays a major role in measuring the longitudinal momentum spread of the bunched ion beams [6], which is one of the most important parameters for beam cooling and precision spectroscopy experiments. However, Schottky spectra of bunched ion beams are very complex, and many simulations have been performed to understand such Schottky spectra. For instance, Betz et al. theoretically analyzed the characteristics of longitudinal Schottky spectra for bunched ion beams recorded at the LHC [7]. Lasocha et al. provide a method to extract the longitudinal and transverse bunch characteristics in the LHC using Schottky-based diagnostics [8,9]. Boine-Frankenheim and Hofmann et al. simulated the Schottky spectra of high-intensity bunched ion beams by considering the influence of the space charge effects [10, 11]. Bussmann et al. simulated Schottky spectra of laser-cooled weakly coupled ion beams in the equilibrium state between heating due to intra-beam scattering and cooling by a laser force [12]. Hasse and Danared et al. successfully explained the anomalous reduction of the longitudinal temperature and Schottky-noise power for the very weak ion beam during the electron cooling process [13, 14]. Even though these simulations provide the fundamental basis for understanding the Schottky spectrum of bunched ion beams, there are still some open questions, such as what causes the greatly enhanced power of the central peak in Schottky spectra and how to extract the momentum distribution of the bunched ions from a Schottky spectrum.

In this paper, we present our experimental and simulation studies to answer these open questions. Both O5+ and Kr30+ ions were used to study the Schottky spectrum of longitudinal bunched ion beams at the experimental Cooler Storage Ring (CSRe) [15]. A multi-particle tracking code

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ELECTRON AND LASER COOLING OF STORED ION BEAMS AT CERN: XSUITE SIMULATIONS AND MEASUREMENTS*

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Abstract

Electron and laser cooling are key techniques for improving the quality of stored beams in synchrotrons. This contribution summarises the main advancements in electron and laser cooling simulations and measurements at CERN, with emphasis on benchmarked Xsuite models and on their application to present and future facilities. On the electron–cooling side, we present the implementation and validation of the Parkhomchuk model in Xsuite and its application to LEIR, ELENA, and to the design of the new AD electron cooler. On the laser–cooling side, we discuss simulations for the Gamma Factory proof–of–principle experiment in the SPS. The interplay between cooling and intrabeam scattering (IBS) is addressed, and we outline operational scenarios and open questions.

INTRODUCTION AND MOTIVATION

Beam cooling is routinely used in several CERN rings. Stochastic and electron cooling provide the deceleration and delivery of high-quality antiproton beams at the Antimatter Factory (AD/ELENA) [1], while electron cooling in LEIR is an essential component of the heavy–ion injector chain feeding the LHC and fixed–target experiments [2]. Ongoing initiatives such as the Gamma Factory proof–of–principle (PoP) experiment in the SPS [3] create a unique opportunity to test laser cooling at unprecedented energies. A unified, predictive simulation environment is therefore needed to study cooling and its interplay with heating mechanisms such as intrabeam scattering (IBS) and space charge in a consistent and quantitative manner.

Xsuite is the current production toolkit for beam dynamics at CERN, gradually replacing a landscape of legacy codes [4]. It provides a modern Python interface, supports heterogeneous computational back-ends (multi-threaded CPUs and GPUs), and follows an agile, community-driven development model with frequent releases. The framework hosts physics modules covering the full range from low-energy hadron rings to high-energy lepton colliders, allowing a wide variety of effects to be simulated within coherent coordinates and conventions. This significantly simplifies combining multiple physical mechanisms and accelerates both the setup and execution of complex simulations.

For these reasons, electron and laser cooling have been implemented directly within Xsuite, taking advantage of its fast development cycle and existing heating modules (e.g. IBS). This enables realistic start-to-end studies of cooling in operational and future CERN machines.

This work provides a concise overview of recent progress in this effort and continues the developments presented in Refs. [5–8]. A more detailed and comprehensive description will be available in the PhD thesis of P. Kruyt [9].

ELECTRON COOLING IN XSUITE

All CERN electron coolers operate in the magnetised regime, with relatively low-energy ($\lesssim$ 30 keV) DC electron beams (currents up to ~ 2.5 A) and longitudinal guide fields in the range of a few hundred gauss (100 G to 750 G). For this reason, the empirical Parkhomchuk friction-force model [10] was implemented in Xsuite, after revisiting the physics as implemented in BETACOOL [11], to ensure correctness and full documentation. A detailed re-analysis of the BETACOOL source code revealed several issues: (i) minor bugs in the handling of space-charge neutralisation; (ii) an inversion of the sign convention for the electron-beam rotation; and (iii) an undocumented coupling between the rotation and the transverse electron temperature. The first two effects have been corrected in the publicly available BETACOOL source [12], while the third was *not* imported into Xsuite, pending further theoretical clarification. Additional details will be provided in [9].

The resulting Xsuite implementation was validated against BETACOOL benchmarks using LEIR-like parameters and scanning a wide set of cooler conditions, including deliberately extreme—and sometimes non-physical—values to stress-test the algorithms. An example is shown in Fig. 1, where the cooling performance is compared over a scan of the cooler magnetic field, probing different regimes contained within the Parkhomchuk model. The agreement between the two codes is remarkable, with only minor deviations attributable to statistical differences in the generated particle distributions. These results provide confidence that the Xsuite implementation is ready to replace BETACOOL for magnetised electron-cooling simulations based on the Parkhomchuk model.

ELENA, AD, AND LEIR APPLICATIONS

The validated Xsuite electron-cooling model has been applied to several CERN accelerator rings.

For ELENA, Xsuite has been used to interpret both longitudinal and transverse cooling measurements, including the characterisation of transverse cooling at the extraction momentum of 13.7 MeV c_0^{-1}. A detailed account of these

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SIMULATION OF LONGITUDINAL ELECTRON COOLING OF 20 GeV PROTON BEAM AT EicC*

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Abstract

The longitudinal electron cooling processes of a 20 GeV proton beam were simulated using a code at the Electron-Ion collider in China. The longitudinal cooling time was obtained for different parameter configurations of the storage ring, proton beam, electron cooling device, and electron beam. From the simulated results, the longitudinal cooling time of the 20 GeV proton beam is over 100 seconds. The longitudinal cooling time can be shortened with the help of proper configuration of the parameters.

INTRODUCTION

Based on the HIAF (the Heavy Ion High-Intensity Accelerator Facility, approved in 2015 in China), a high luminosity polarized Electron-Ion Collider facility in China (EicC) has been proposed to study hadron structure and the strong interaction to carry out the frontier research on both nuclear and particle physics.

EicC will be constructed in two phases, EicC-I and EicC-II. In the first phase, a proton beam with energy between 15–20 GeV will collide with an electron beam with energy between 2.8–5 GeV. Both electron and proton beams are polarized. The luminosity is expected to reach 2–4×10^{33} $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$.

In the second phase, the energy of the proton will be upgraded to 60–100 GeV, and the energy of the electron beam will be increased to 5–10 GeV, with luminosity expected to reach 1×10^{35}. The primary design and some initial parameters of EicC are found in Ref. [1].

To obtain the expected luminosity in the collider, the polarized proton beam will be cooled by various cooling methods throughout the entire operational energy range. Especially in the case of high-intensity energy proton beams, the intra-beam scattering effect should be considered in the collider design. The transverse electron cooling and intra-beam scattering were presented in the Ref. [2]. Some preliminary simulations of longitudinal electron cooling are presented in this contribution.

SIMULATION OF ELECTRON COOLING

The longitudinal electron cooling time depends not only on the lattice parameters of the storage ring, such as the Betatron function, dispersion of the cooling section, parameters of proton beam including energy, initial emittance, and momentum spread, but also on the construction parameters of electron cooling device, including the strength of magnetic field, the parallelism of magnetic field in the cooling section, the effective cooling length, and the parameters of electron beam, such as radius, density and transverse temperature of electron beam. These parameters are determined by the storage ring and the technology limitation, on the other hand, they are influenced and restricted by each other.

Among these parameters, the first type of parameter determines whether the proton beam under such parameters can be cooled down, playing a decisive role. The second type of parameter determines the length of cooling time for the proton beam under such parameters, playing an optimization role.

Using the electron cooling simulation code SIMCOOL [3, 4], the longitudinal electron cooling time of the proton beam was extensively simulated in various parameters in the EicC, including proton beam energy, initial transverse emittance, and momentum spread. The influence of the machine lattice parameters such as the Betatron function and dispersion function the cooling time was investigated. The parameters of the electron beam and cooling devices were taken into account, such as effective cooling length, magnetic field strength and parallelism in the cooling section, and electron beam current.

The different performances in transverse and longitudinal directions were observed compared with the traditional low-energy electron cooling.

The variation of momentum spread over time does not follow an exponential decay form, making it impossible to fit the cooling time. During the fitting process, either the decay curve does not match, or the final equilibrium value does not match. It decays faster than the exponential decay.

The fitting can only be performed on the first half of the data, while the second half corresponds to the scattering process. The other time it takes for momentum spread to reach its minimum.

As mentioned in the previous paragraph, the proton beam was cooled in the transverse direction. The longitudinal cooling process differs from the transverse one. During the initial cooling, the momentum spread drops rapidly and then gets to the minimum. And then the momentum spread starts to grow, rebounding from its minimum. The proton beam was not cooled when the energy shift of the electron beam was larger than a certain value.

In the longitudinal direction, due to the cooling happened first, and then scattering happened later. So only the cooling part was fitted. The longitudinal cooling time was replaced by the time when the momentum spread reached its minimum.

Proton Beam Parameters

Typical longitudinal cooling processes are illustrated in Figure 1 (left).

The right diagram of Figure 1 shows the longitudinal electron cooling time as a function of the particle number in the proton beam. In the case of other parameters that

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VERSATILE PLATFORM FOR RELATIVISTIC ELECTRON COOLING AND OTHER EXPERIMENTS

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Abstract

At Helmholtz-Institut Mainz (HIM) a high voltage platform for high intensity electron beams has been installed. This apparatus is intended as a scalable, modular system for high energy magnetized DC-beam cooling. On the one hand, the system can be used as a prototype for antiproton beam cooling for the planned HESR storage ring at FAIR. On the other, because the HESR will be delayed, we have the opportunity to use the device for other applications. We present recently realized technical progress and how these can be applied for different new experiments during the time until the initially intended application becomes possible.

INTRODUCTION

Helmholtz-Institut Mainz (HIM) is a joint venture of the Johannes Gutenberg-University in Mainz and the national research lab GSI (GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany). The latter is presently installing several accelerators of the FAIR (Facility for Antiproton and Ion Research) complex on its premises.

At the beginning of the 2010-decade, HIM had taken over responsibilities for a relativistic electron cooler which is to be used at the High Energy Storage Ring (HESR), where the majority of the antiproton experiments at FAIR are planned. This will happen in particular by interaction with a fixed target within the $\overline{\mathrm{P}}$ANDA experiment. The strong interaction with its target necessitates magnetized electron cooling with a very high intensity at kinetic energy of almost 8 MeV. A cooperation between Budker Institute Novosibirsk (BINP) and HIM was started to investigate the challenges associated with this task.

An important part of the developments done at HIM has been concentrated on a sustainable floating power supply for the magnetization solenoids in the acceleration/deceleration channel of the cooler. A gas turbine based system has been installed at HIM which solves this problem producing power of several kilowatts at high potential, see for instance [1]. The next goal was a prototype device which has two 600 kV units in order to demonstrate the scalability comprising two identical HV-platforms, each containing a single gas-turbine [1]. These platforms were to be produced by BINP, but only one has been delivered before the war in Ukraine has stopped the cooperation.

Another important point to take into account is that the construction of the HESR-building has not yet begun, which means that HESR will not be operated within the present decade. This opens up the question which research can be done at HIM in the meantime while not compromising the goals relevant for electron cooling.

In the next sections we will first describe the present status of the cooler activities and then present two projects which will permit us to sustain competences and knowledge until the timeline for electron cooling at HESR becomes more predictable. A first one which is already producing promising results is using high power electron beams of similar intensity as in the cooler for medical purposes. Another potential project is to use the existing cooler-prototype to develop techniques which can be used to make precision measurements of a possible electric dipole moment (EDM) of electrons.

STATUS OF THE ELECTRON COOLER PROTOTYPE

The power for the solenoids which magnetize the beam is provided by a turbo-generator which expands 3 bar nitrogen gas. The gas is used in a closed circuit which is driven by a screw compressor. All units of the circuit are commercial devices. The gas circuit was designed by Prof. M. Wirsum from the institute for gas driven power stations at RWTH Aachen. After setting the mass flows with regulation valves at constant load, the system runs stable without further intervention. The turbine gas-system is separate from the pressure tank. In summer 2025 the tank itself was sealed and filled with 3 bar of nitrogen. Leak rate was observed to be about 0.1 bar/week which is no limit for present experimentation but needs to be improved if typical insulation gases such as SF_6 would be used.

The communication with the HV-platform is based on software delivered by BINP. After some trial and error, communication could be set up. The turbo-generator permitted to power the solenoid on the platform and also the Cockcroft Walton HV-generator. This voltage could not be increased to more than 80 kV, we suspect an internal hardware safety limit. No sign of corona discharges was observed at this voltage. This seems reasonable since the air gap between the inner wall of the tank and the outer radius of the platform is about 50 cm (see Fig. 1), which should provide sufficient insulation for even the maximum voltage of the HV-generator (600 kV) at our 3 bar nitrogen pressure. The next step is to "reverse engineer" the control of the Cockcroft-Walton to circumvent the present limit.

Summarizing the situation, it can be stated that the device is now ready for experimentation which can go in several directions, for instance to demonstrate the scalability of the

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GUN AND COLLECTOR DEVELOPMENT ON THE ELECTRON COOLER TEST STAND (ECTS)

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Abstract

The electron cooler of the Antiproton Decelerator (AD) at CERN, that can operate with an electron beam of up to 2.4 A at 27 keV, is scheduled for replacement during the upcoming Long Shutdown 3 (LS3). A newly designed electron gun and collector—optimized for enhanced reliability, efficiency, and operational performance—are undergoing rigorous testing and validation at the dedicated Electron Cooler Test Stand (ECTS). The new electron collector features a re-engineered cooling system, where the water circuit is fully decoupled from the vacuum environment, significantly reducing the risk of vacuum leaks. The new electron gun operates at high perveance in the range of 2.2 to 2.5 $\mu\text{A}\cdot\text{V}^{-3/2}$ and employs a magnetic beam expansion by a factor of two. This expansion lowers the transverse temperature of the electron beam, thereby enhancing the cooling efficiency. This paper will present the ongoing research, key design considerations, and the latest experimental results from the ECTS, contributing to the successful implementation of the new AD electron cooler.

INTRODUCTION

Electron cooling, first introduced by G. Budker in 1966 [1], is a standard technique for reducing beam emittance and improving beam quality. The present AD electron cooler originates from the Initial Cooling Experiment (ICE) at CERN [2], was later adapted for LEAR [3] and finally integrated into the Antiproton Decelerator [4]. After decades of operation many components have reached end-of-life and critical spares are no longer available, motivating the development of a new electron cooler for the AD [5,6].

A new high-performance electron gun has therefore been designed, prototyped and tested. Its geometry was derived from detailed electron-beam simulations to meet the requirements of 2.4 A at 27 keV. This paper focuses on the development, optimisation and characterisation of this gun and its integration with the redesigned collector. A description of the legacy gun and collector used in the existing AD cooler can be found in Refs. [7,8].

EXPERIMENTAL SETUP

The characterization of the prototype electron gun and the validation of the redesigned collector were performed on the Electron Cooler Test Stand (ECTS), a dedicated high-voltage platform developed at CERN for testing electron cooler components at DC high voltages of up to –80 kV, see Fig. 1. A detailed description of the facility is available in Ref. [9]; only a short summary is given here.

The ECTS consists of a fully enclosed Faraday cage on an elevated high-voltage platform, powered by an 80 kV / 50 kW three-phase isolation transformer. All gun and collector power supplies are located on the HV platform, while magnet power supplies and supervisory computers remain at ground potential. Communication is via optical fibre links and Wi-Fi. The system is operated through a Python/LabVIEW-based control suite providing slow control, data logging, vacuum diagnostics and interlock handling.

The test line includes a 1.5 m solenoid capable of generating up to 900 G, a squeeze coil at the collector entrance, and a magnetic shield surrounding the collector chamber to minimise electron losses. Current and voltage measurements are performed using precision shunt resistors on the gun and collector return lines. Vacuum is maintained by a combination of a turbomolecular pump backed by a dry scroll pump, an ion pump, a NexTorr pump and a titanium sublimation pump, reaching base pressures of a few 10^{-10} mbar at the collector after bakeout. During hot-cathode operation and beam extraction, the pressure typically rises into the low 10^{-8} mbar range.

A dedicated low-conductivity cooling-water circuit removes heat from the electron collector during beam dump. The loop includes resin filters and continuous purification to maintain low conductivity for high-voltage operation and to minimise leakage currents to ground. The redesigned collector has already been tested and validated [10]; the present work concentrates on the prototyping and iterative development of the new electron gun.

GUN PROTOTYPE AND TESTS

Informed by detailed particle-tracking simulations in EGUN, TRAK and CST [12,13,15], a high-perveance electron gun was developed to meet the specifications of the new AD electron cooler: 2.4 A at 27 keV in a 2400 Gauss magnetic field at the gun, matched to a ~ 600 Gauss field in the cooling region. This yields a magnetic expansion of the beam radius by a factor two, from 12.5 mm at the cathode to 25 mm in the cooling section. Several cathode surface shapes—flat, concave and convex—were investigated in simulations to minimise transverse temperature while preserving perveance in the range 2.2 $\mu\text{A/V}^{1.5}$ to 2.5 $\mu\text{A/V}^{1.5}$.

Guided by these results, a first prototype gun was designed and built with the aim of validating the electrodes geometry, demonstrating emission at 27 keV and 2.4 A, checking insulation up to 30 kV with a hot cathode and identifying

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PROGRESS TOWARDS A FIELD EMISSION ELECTRON GUN FOR THE ELENA ELECTRON COOLER

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Abstract

Field emission-based cathodes have been shown to be an attractive alternative to thermionic sources for the generation of electron beams. Their low transverse energy spread, and low power consumption make them an ideal replacement for the thermionic cathode currently used on the electron cooler of the Extra Low ENergy Antiproton (ELENA) ring.

We have investigated the use of carbon nanotubes (CNT) as the field emitting source, studying the emission characteristics and lifetime of various patterned structures. Fowler-Norheim analysis of our samples has given us a better understanding of the limiting factors of such sources, especially the influence of the conditioning process on the emitted current.

A double-gridded electron gun has also been tested with CNT samples of various sizes up to 4×4 cm. The measured current density for the larger samples was somewhat lower that expected and showed a larger beam divergence than what was predicted by the simulations. This discrepancy is currently under investigation as well as improvements to the gun design to obtain stable and reproducible beams.

INTRODUCTION

In ELENA, electron cooling is fundamental to reduce the emittance blow-up of the antiproton beam so that a focused and bright beam can be delivered to the experiments [1]. Presently, the electron gun relies on thermionic emission, where a tungsten-doped barium oxide (BaO) source is heated to 1200 °C. However, this imposes several limitations on the transverse beam energy and the required magnet system. A cold emission-based electron gun might overcome these constraints, as field emission relies solely on high electric fields to both generate and control the electron beam.

WHY CARBON NANOTUBES?

Despite field emission being a known effect since 1928 when first proposed by Fowler and Nordheim [2], it has only recently become a flourishing field of research thanks to the technological progress that has opened to the possibility of creating 2D nano-structures. 2D nano-materials can have greatly enhanced field emission properties and allow to extract relatively high currents (usually tens of mA/cm^2) at relatively low applied electric field (some V µm^{-1}) [3]. This is possible thanks to a field enhancement at the nano-structure surface, usually described by means of the so-called field enhancement factor β.

For our development, CNTs have been chosen due to their remarkable properties in this field. They are nowadays considered among the most promising material for field emission, reaching high current densities, being largely chemically inert and having a good emission stability. Several groups have reported promising results using arrays of vertically aligned CNTs. Such an arrangement minimizes the screening effect which usually severely affects the performance of forests and disordered structures.

EXPERIMENTAL SETUP

The Cold-Cathode-Test-Bench (see Fig. 1) has undergone a major upgrade since the initial measurements and now encompasses the gun assembly installed in a vacuum tank mounted on a 6-way cross. Three flanges are dedicated for the Edwards Vacuum Pump and Pfeiffer TPG 362 Dual Gauge, a Vacom Novion vacuum sensor and a PHOTONIS Ion Beam Profiler (IBP). A three sample holder is installed on the final flange for testing the emission characteristics of individual carbon nanontube structures.

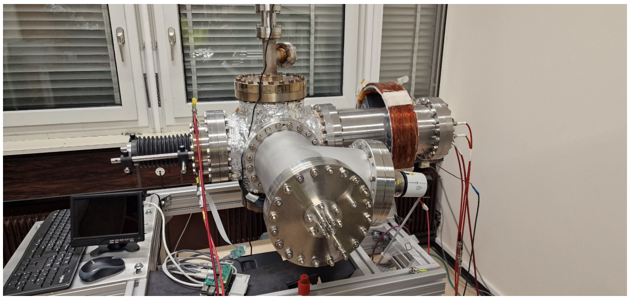

Figure 1: Cold Cathode Test Bench (CCTB)

CNT SAMPLE MEASUREMENTS

In previous studies we investigated the emission stability and lifetime of patterned CNT arrays purchased from NanoLab Inc. [4]. We concluded that hexagonal structures were best suited for our application, giving relatively high emission currents with good long-term stability.

A new set of CNTs of various dimensions was obtained from the International Iberian Nanotechnology Laboratory (INL, `https://inl.int/`) in Braga, Portugal. Hexagonal CNT arrays of 10 µm side and 20 µm height spaced by 3 µm (see Fig. 2) were grown by chemical vapour deposition (CVD) on silicon wafers and diced to the required dimensions [5]. Samples were first conditioned and characterised on the measurement flange and then transferred to the gun for beam profile measurements. The conditioning consists in slowly ramping the voltage to a fixed value whilst monitoring

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STOCHASTIC COOLING ENHANCED STEADY-STATE MICROBUNCHING

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Abstract

In this paper, we propose to combine two promising research topics in accelerator physics, i.e., optical stochastic cooling (OSC) and steady-state microbunching (SSMB). Our study shows that such an OSC-SSMB storage ring with a circumference of 50 m and beam energy of several hundred MeVs using present technology can deliver kilowatt radiation at 100 nm wavelength. A more ambitious application of OSC in an SSMB ring can push the radiation wavelength to an even shorter wavelength, such as EUV and soft X-ray. Such a powerful compact light source could benefit fundamental science research and industry applications.

INTRODUCTION

Steady-state microbunching (SSMB) [1–3] scales the bunching mechanism in a storage ring from the conventional microwave or radio-frequency (RF) region to optical wavelengths to generate ultrashort electron bunches on a turn-by-turn basis for high-power short-wavelength coherent radiation generation, and its proof-of-principle experiment has been successfully conducted recently at the MLS storage ring [4,5]. Optical stochastic cooling (OSC) [6,7] is a scaling of the conventional stochastic cooling scenario from the microwave to optical frequency range to speed up the damping of particle beam emittance. Its mechanism has also been demonstrated recently in the IOTA storage ring [8,9]. One interesting idea is then to combine them, which hopefully can relax the technical requirements and enhance the capabilities of an SSMB radiation source.

SSMB SCENARIOS

SSMB is a general concept and there are several specific scenarios for its realization. Here we group these scenarios into two categories, i.e., globally microbunching schemes and locally microbunching schemes.

Globally Microbunching / Longitudinal Focusing

For globally microbunching or longitudinal focusing schemes, it means the electron beam is microbunched all around the ring. Generally, these SSMB schemes require the storage ring to work in a quasi-isochronous or low-alpha mode. The laser modulators are used in a way similar to that of RF cavities in a conventional storage ring, i.e., to longitudinal focus the electron beam to make it become microbunched. The microbunches are thus separated with a distance of the modulation laser wavelength. Note that due to the impact of local phase slippage factor and transverse-longitudinal coupling [2], the microbunch length can vary significantly around the ring. The microbunching here therefore more accurately refers to microbunching in phase space. Depending on the strength and mechanism of longitudinal focusing, we have developed three such SSMB scenarios in the past years, namely longitudinal weak focusing (LWF), longitudinal strong focusing (LSF) and generalized longitudinal strong focusing (GLSF) [10, 11], as schematically shown in Fig. 1. For a comprehensive analysis of their beam physics, the readers can refer to Ref. [11].

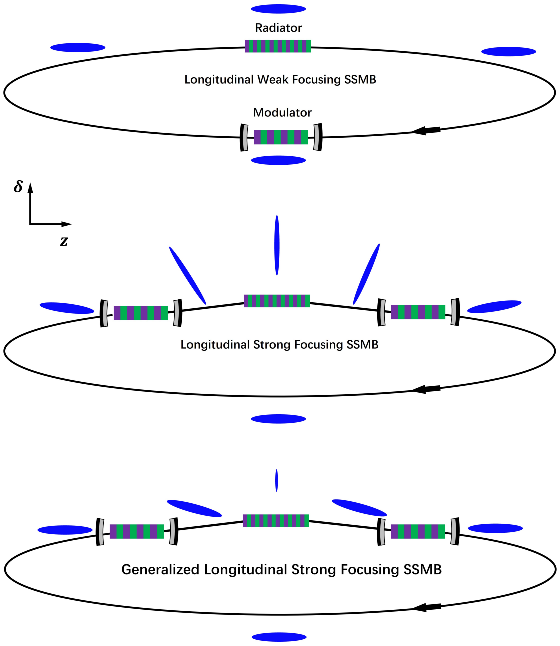

Figure 1: Schematic layouts of a longitudinal weak focusing (top), longitudinal strong focusing (center) and generalized longitudinal strong focusing (bottom) SSMB storage ring.

For globally microbunching schemes, the key is to realize a small equilibrium beam emittance. At least one of the three eigen emittances should be ultra-low to realize ultra-short electron bunch with a mild requirement on the modulation laser power. For LWF and LSF SSMB, it is the longitudinal emittance, while for GLSF SSMB it is the vertical emittance.

Locally Microbunching / Reversible Modulation

For locally microbunching schemes, it means microbunching appears only in a limited section in a storage ring. Outside that limited region, the electron beam is just a conventional bunch, which means it can be an RF bunch, or even a coasting beam. A representative method to realize locally microbucnhing is using a downstream reverse laser modulation to cancel the modulation imprinted in the upstream laser modulator, and microbunching only appears at the radiator in between [12, 13]. By invoking such a

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ION MACHINE-GUN EXPERIMENT AT HIROSHIMA UNIVERSITY*

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Abstract

Ion beams with micrometer-order spot size, so-called “microbeams,” have been utilized in a variety of fields. These include the biological response of radiation in cells and the single event effects of a semiconductor, etc. On the other hand, certain applications, such as the creation of a color center in a diamond, require an ion beam with not only the higher precision of a nanometer-order diameter but also the ability to implant ions one by one. The ion machine gun (IMG) is the possible choice for the realization of this distinctive ion beam. It is mainly composed of a linear Paul trap (LPT) and Doppler-cooling lasers. Ions laser-cooled to nearly absolute zero in the LPT reach a “Coulomb crystalline state.” If we extract ions in this state without heating, a unique ion beam can be attained. Most ion species, even if they cannot be directly laser-cooled, can be cooled sympathetically and crystallized through Coulomb collisions with laser-cooled ions simultaneously confined in the LPT. At Hiroshima University, we conduct proof-of-principle experiments of the IMG using laser-cooled calcium ions and sympathetically cooled nitrogen ions. Here we discuss the fundamental principle and experimental results of this study.

INTRODUCTION

Various types of charged-particle beams, differing in particle species, kinetic energy, or intensity, are used depending on their purpose. Among these is the *microbeam*, which is focused down to the micrometer scale. Microbeams are used, for example, in studies of biological response to radiation in cells [1] or in research into errors caused by charged particles entering semiconductors [2]. Generally, microbeams achieve a micrometer-order spot size by narrowing the beam using collimators or focusing lenses. How tightly the beam can be focused is determined by the beam’s emittance. The emittance is defined as a volume in the 6D phase space occupied by particles constituting the beam. The lower the particle beam’s emittance, the smaller the particles’ positional and momentum divergence, which means the better the beam's quality.

Reducing the emittance with a dissipative force is called *cooling* because it is physically equivalent to lowering the beam temperature. If ions are cooled to near absolute zero, the Coulomb interaction between each ion and the external confinement force reaches equilibrium, and the relative position of each ion does not change. This state is called *Coulomb crystal*, which is the ultimate low-emittance state of the ions. Among beam-cooling techniques, *laser cooling* is the only one that can crystallize ions so far. However, crystallizing a beam rapidly circulating in an accelerator is difficult because the laser cooling force is not very effective in the direction perpendicular to the laser, and a strong dispersive heating effect occurs due to bending magnets.

On the other hand, crystallizing ions confined in an ion trap is much easier than a beam in an accelerator. The “Ion Machine Gun (IMG),” which utilizes a Coulomb crystal in an ion trap as a beam source, is a possible choice for realizing an ultra-low-emittance beam [3]. Coulomb crystals form different structures depending on their line density. At low line densities, ions line up in a single row along the axis of the trap, forming what is called *string* crystal. As the line density increases, they form a *zigzag* crystal, and with an even higher density, they become a *shell* crystal structure. If ions are extracted from an ion trap one by one without serious heating, we can obtain a unique beam whose emittance is on the order of femtometers or less, and the spot size can be focused on the nanometer scale [4, 5].

Although laser cooling can only be applied to a limited number of ion species with specific energy levels, any ion species can, in principle, be sympathetically cooled through Coulomb interactions with laser-coolable ions. A European research team conducted an experiment to extract a nitrogen molecular ion ($^{14}N_2^+$) from a Coulomb crystal composed of a laser-coolable calcium ion ($^{40}Ca^+$) and sympathetically cooled a $^{14}N_2^+$ ion [6].

We are conducting research and development to extract a single nitrogen ion with very low emittance, applying the IMG idea. In what follows, we introduce our experimental system employing a linear Paul trap (LPT) and a new extraction method employing a shell Coulomb crystal. We also report the results of some numerical tests and experiments for proof-of-principle of the method.

PAUL-TRAP ION SOURCE

Experimental Setup

The LPT used in the experiment has a conventional structure with quadrupole rods and three end-plate electrodes. Figure 1 shows an image of the LPT. Each rod electrode measures 6.88 mm in diameter, 88 mm in length, and 3 mm from the trap axis. The amplitude of radiofrequency (rf) voltage ($V_{\rm rf}$) is 30 V or lower, with an operating frequency of 2 MHz. Three end-plate electrodes (End-A, End-B, and End-C) with a uniform thickness of 12 mm are

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PROPOSED ULTRALOW-EMITTANCE BEAM SOURCE FOR HIGH-LUMINOSITY HADRON COLLIDERS*

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Abstract

Laser Doppler cooling of ion bunches in a Paul trap is a demonstrated method of achieving millikelvin bunch temperatures, with the ions forming a Coulomb crystal with a solid-like structure. This is proposed as a source for accelerators that would be a factor 10^5 lower in emittance than conventional plasma sources. Methods to transport the crystalline bunch while limiting emittance growth are examined, including a novel ring in which the bunch maintains a fixed orientation relative to the outside world (i.e. does not rotate with the ring as usual). In this geometry, magnetic focussing can confine all three dimensions of the bunch without RF. This ring can circulate a 3D crystalline bunch with heating rates of less than 1 K/s.

LASER COOLED ION TRAPS

Laser Doppler cooling is an established method for studying atoms and ions at low temperatures [1]. Several trap geometries can be used with this method but the linear Paul ion trap, with DC electrostatic confinement longitudinally and ~MHz range RF quadrupole transversely, has been used for accelerator applications. The SPOD experiment [2] at Hiroshima University has prepared Ca^+ Coulomb crystals at rest, where the individual ions have vibration velocities of a few m/s and can be seen in a fixed lattice via their fluorescence light during cooling [3]. A Paul trap without cooling has also been built for accelerator physics reasons in the IBEX experiment [4] at Rutherford Appleton Laboratory, where the resonances of the ion cloud under space charge forces can be studied.

Cooling Simulation

A simulation code that runs on the GPU using OpenCL has been written to simulate cooled ion traps. 4th order Runge–Kutta steps in the trap potential are interleaved with pairwise space charge kicks. The ions have a ground and an excited state, the transitions between them governed by a statistical model whose rates agree with the quantum description of a two-level atom in a laser beam. These excitations and de-excitations come with appropriate $\Delta p = \hbar k$ momentum kicks, where it is important to apply the events at truly random points within each timestep, so the short periods where the Doppler process is active are not jumped over.

The results of such a simulation are shown in Figure 1, where the eventual configuration of ions was a long Coulomb crystal several ions wide. Two phases of cooling can be seen: the first occurs before formation of a solid Coulomb crystal core from the initially gas-like ions, while the second ends when the small fraction of remaining ions ‘orbiting’ the solid core eventually lose enough momentum to merge with it. The final temperature is a small multiple of the predicted Doppler limit ($T_D = 0.552$ mK here). The RF nature of the transverse focussing excites some vibrations that take the temperature above the limit.

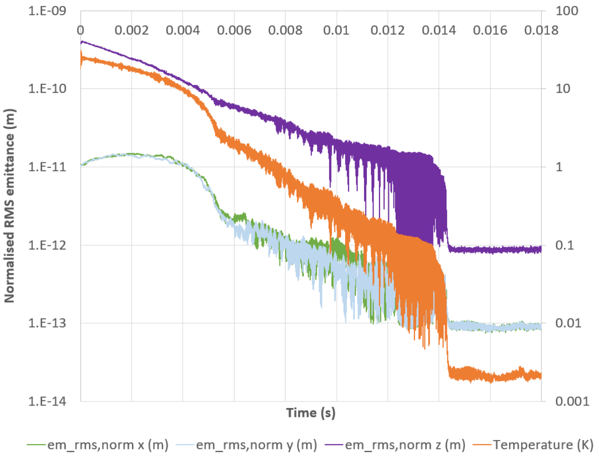

Figure 1: Laser Doppler cooling simulation with $N = 500$ ions.

The final emittances are very small. For a shorter trap producing a spherical bunch, the scaling

$$\frac{\sigma_{x,y,z}}{N^{1/3}} \simeq 25\,\mu\mathrm{m},$$

$$\frac{\epsilon_{x,y}}{N^{1/3}} \simeq 7\times10^{-14}\,\mathrm{m}, \qquad \frac{\epsilon_z}{N^{1/3}} \simeq 4\times10^{-14}\,\mathrm{m}$$

was observed in simulations from $N = 100$ to 81920 ions, where ϵ denotes normalised RMS emittance. The crystal temperature was consistently ~3 mK. This emittance is related to temperature via $\epsilon \simeq \sigma_x \frac{\sigma_v}{c} = \frac{\sigma_x}{c}\sqrt{\frac{k_B T}{m}}$.

Increasing Throughput

The maximum possible ion population in existing traps is around 10^7 [2, 5]. With the cooling time of up to 20 ms, a 50 Hz repetition rate source would give an average current of only 80 pA. However, existing sources are not optimised for throughput. The trapping electrode voltages are typically 150 V or lower, which could be increased by two orders of magnitude with a high voltage setup, allowing 10^9 ions to be trapped. A more drastic improvement would be possible using a linear cooling channel, where multiple bunches move along at ~10 km/s so that by the end of a ~200 m-long (possibly coiled) channel they would have completed cooling. This channel would resemble an RFQ but operate at

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ELECTRON BEAM DYNAMICS SIMULATION IN COHERENT ELECTRON COOLING

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Abstract

New scheme with lower electron beam energy together with lower peak beam current has been proposed for the Coherent electron cooling (CeC) proof of principle experiment in RHIC Run 25 [1]. Such new operation mode appears to be a better candidate in providing a high-quality beam for cooling performance. In this paper we will present our results to achieve the low slice emittance/low slice energy spread electron beam and discuss the progress in achieving better uniformity in both average slice energy and slice peak current to minimize potential anti-cooling effect.

INTRODUCTION

The CeC beamline (Figure 1) consists of low energy beam transport (where electron beam is prepared and accelerated to a total energy of 10 MeV), a dogleg section to transport the beam to a common section where the electron beam is co-propagating with the hadron beam. In the common section, the electron beam is matched to beam requirements in cooling section where the electron beam co-propagates with the hadron beam.

The performance of the cooling is highly dependent on the electron beam's quality. Thus, a self-consistent start to end (S2E) simulation of the accelerator section is crucial in determining the amplifier's performance and in predicting the machine setups to characterize the cooling.

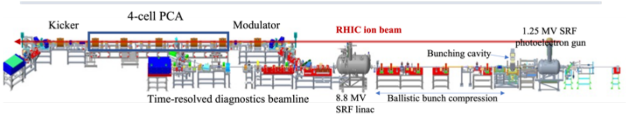

Figure 1: Engineering drawing of CeC beamline (electron beam travels from right to left).

LOW ENERGY BEAM DYNAMICS

There are three RF systems in the CeC's accelerator section – a quarter-wave SRF gun cavity (1.25 MeV, 113 MHz), a NC bunching cavity (tunable for different peak current, usually at about 140 to 160 keV, 500 MHz) and a 5-cell SRF linac (up to 13.5 MeV, 704 MHz). All three RF systems are operated at harmonics of a global clock, 78 kHz – the RHIC's revolution frequency. In between cavities, 6 solenoids are used for electron beam's phase space manipulation and beam size control. More specifically, the solenoid in between gun cavity and the linac is used to perform emittance compensation, i.e., provide optimal transverse focusing to minimize emittance growth from space charge effect of low energy electron beam, which is illustrated in Fig. 2. After the beam gains energy chirp from bunching cavities and experiences ballistic compression in long straight section (~ 10 m to linac), the beam current increases to ~ 20 amps prior to entrance into linac where the space charge effect is dominating. In additional, we alternate the polarity of the 5 solenoids in this 10-m long drift to control any systematic field errors and maintain the initial coordinate systems so that the lowest order chromatic effect introduced by misalignments in magnets is compensated. The beam size is focused and matched to optimal beam conditions at the entrance of the linac.

There are many different beam dynamics in the beam line that could potentially affect beam qualities severely, namely space charge, wakefields, shielding effect from vaccum chamber etc. Doing all beam dynamics in one simulation code is unimaginable. We used many dedicated codes to calculate these effects before importing the simulated results into the IMPACT-T [2] to track particles' 6D evolution along the beamline. We benchmarked our calculated beam properties (like beam envelope, phase space distributions, energy evolutions) in IMPACT-T with many other well established beam dynamics codes e.g., GPT/PARMELA/ASTRA.

We recessed our cathode position in the gun cavity so that the initial RF field provides a strong transverse focusing to the beam. With adjusted cathode recess position, the proper focusing force can be selected to better suit beam dynamics in the gun.

As mentioned above, we used a bunching cavity to provide energy chirp in the low energy beam (~ 1.25 MeV kinetic energy) for the beam to undergo a ballistic compression in the long beam transport prior to getting a major boost in energy in the 704 cavity (~ 8.4 MeV kinetic energy gain). The energy distribution in different beam slices will have different rotation in solenoids which are used to provide focusing. Such process smears out the transverse phase space and by carefully tuning up the solenoids, the longitudinal slices along the beam are aligned in the phase space to reduce the projected emittance as well as the variation of the optics functions along the slices at the end of the low energy beam line. Detailed plots of the transverse phase space evolution can be visualized from particle tracking in IMPACT-T shown in Figure 2.

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MULTIPLE-SLICE SIMULATIONS OF COHERENT ELECTRON COOLING PERFORMANCE WITH LOW BEAM CURRENT[*]

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Abstract

Coherent electron cooling (CeC) is a novel technique for rapidly cooling high-energy, high-intensity hadron beam. Plasma cascade amplifier (PCA) has been proposed for the CeC experiment in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Cooling performance of PCA based CeC has been predicted in 3D start-to-end CeC simulations using code SPACE for multiple slices in the beam. The operation of low beam current provides more flexibilities for the CeC experiment.

INTRODUCTION

Coherent electron cooling (CeC) [1–3] is a promising technique for the rapid cooling of high-energy high-intensity hadron beams in modern accelerators. In this paper, we present simulation studies of the CeC with plasma cascade amplifier (PCA) [4, 5], which utilizes the plasma cascade instability (PCI) [6–9]. Our simulation tool, the SPACE code [10] has been used in the simulation studies for the mitigation effect by beam induced plasma [11], the modulation process in CeC [12–15], CeC with free electron laser (FEL) amplifier [16–19] and the CeC with PCA [20–23].

Figure1 shows the layout of the CeC system installed in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Our simulation study is based on the CeC experiment and consists of four steps: 1) Design - perform CeC simulations including modulator, PCA, kicker to search for proper beam parameters; 2) Implement - perform beam dynamic simulation including superconducting radio frequency (SRF) gun, low energy beam transport (LEBT), SRF linac dogleg to match the required beam parameters at the entrance of modulator; 3) Predict - perform CeC simulations to predict cooling force with electron beam from beam dynamic simulation; 4) Verify - perform ion tracking simulation to predict ion beam evolution with the presence of CeC.

DESIGN

In the PCA-based CeC shown in Figure2, solenoids are used to modulate the transverse size of the electron beam and to excite the PCI. According to PCI theory, beam peak current and emittance should be carefully chosen to ensure high gain, as is shown in Figure3. Based on the PCI theory, two setups with high beam currents have been developed, as shown in Figure4. Recently, new setups with low beam current have been developed, which demonstrates high PCA gain, as is shown in Figure5.

IMPLEMENT

After a detailed studies on all setups, we have decided to perform beam dynamic simulations to match the low beam current setup, as this setup provides better chance to achieve key performance parameter (KPP) in the CeC experiment. Figure6 shows the beam parameters at the entrance modulator. The beam dynamics simulation is performed with code Impact-T [24].

PREDICT

To predict the cooling force, we have simulated multiple slices of the central beam, with slice duration 2.3 ps, through the PCA-based CeC section. Three PCA lattices have been developed to support the CeC experiment. In each setup, we have tracked the cooling force to ions with reference / off-reference energies, as well as with / without transverse offsets. Dependence of the cooling force amplitude on the transverse offset has been characterized. We have taken the weighted sum of cooling force at transverse offsets with corresponding 2D Gaussian distribution probability density function, to quantify overall cooling force. The ion beam is expected to have normal distribution in transverse plane with RMS beam size 1 mm. The cooling force from the three setups are presented in Figure 7, 8, 9.

VERIFY

Ion beam profile evolution has been tracked in simulations with / without the presence of CeC. Slice 24 to 30 of electron beam from setup 1 has been used to provide cooling. The cooling result is presented in Figure 10 and 11.

SUMMARY

Beam parameters of low peak current for PCA-based CeC have been established. PCA gain spectrum has been simulated, and agrees well with theoretical prediction. Beam dynamic simulation has achieved required beam parameters at the entrance of modulator, with low emittance, low energy spread, uniform β function and αfunction, good symmetry in transverse plane. CeC simulation has predicted strong cooling force because of good quality beam from beam dynamic simulation. Three PCA lattices have been designed

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SIMULATION OF THE ION BUNCH IN THE PRESENCE OF THE CEC FOR THE NEW ENERGY SCHEME*

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Abstract

For RHIC run 25, the beam energy of the Coherent Electron Cooling (CeC) experiment will be reduced to achieve better cooling performance. For the new scheme, the distribution of the cooling electrons is obtained from beam dynamics simulation using Impact-T. A 3-D particle in cell (PIC) simulation code, SPACE, is then used to obtain the cooling force that acts both on the longitudinal and transverse location of the circulating ions. In this study, we track the ions in the presence of the cooling force and investigate how their distribution evolves during the cooling process.

INTRODUCTION

For the past decade, the demonstration experiment of the coherent electron cooling (CeC) has been actively pursued in the Relativistic Heavy Ion Collider (RHIC). To predict the evolution of the ion bunch in the presence of the cooling, a tracking code was developed and benchmarked with numerical solution of the Fokker-Planck equation [1]. The original code assumed a universal cooling force for all ions overlapping with the cooling electrons. If the properties of the electrons vary significantly within the bunch, the cooling force seen by an ion, in general, depends on its 3-D location within the electron bunch. Recently, we have improved the tracking code by implementing the dependence of the cooling force on the 3-D position of the ion.

In the next section, we show the beam parameters and cooling force obtained from the SPACE simulation. The evolution of the ion bunch profile as predicted by the tracking codes is shown in the section “Results of the Ion Tracking”.

PARAMETERS AND COOLING FORCE

Parameters

Before RHIC run 25, the beam energy for the plasma cascade amplifier (PCA) based CeC was γ=28.5 and the required peak current of the electron beam was 50 A [2]. Although the required beam parameter was achievable for some portion of the electron bunch, it was difficult to achieve a uniform region of 15 ps of duration with sufficient beam quality to satisfy the cooling requirement. As a result, a new scheme with beam energy of γ=19.5 was proposed. The new scheme requires 20 A of peak current with the normalized RMS slice emittance of 1.25 µm. After extensive simulation studies and experimental verification, it becomes clear that the new scheme is better suited to demonstrate CeC and it is currently the baseline for the CeC experiment in RHIC run 25. The parameters for the ion beam are shown in Table 1. Table 2 shows the targets for the parameters of the electron beam. Since the local parameters of the electrons vary along the bunch, the 6-D distribution of the electrons from the beam dynamic simulations are used in the single pass particle-in-cell (PIC) simulation to generate local cooling forces.

Table 1: Ion Beam Parameters for the CeC Experiment

Parameters	Ion beam
Energy, γ	19.5
Bunch intensity	2×10^8
RMS bunch length	2 ns
RMS emittance, normalized	2.5 µm
RF frequency	28 MHz
RF voltage	4.3 MV
Average beta function at IR2	11 m
Average RMS beam size	1.2 mm

Table 2: Electron Beam Parameters for the CeC Experiment

Parameters	Electron beam
Energy, γ	19.5
Bunch charge	0.8 nC
Peak current	20 A
RMS emittance, normalized	1.25 µm
RMS energy spread	$< 2 \times 10^{-4}$
Bunch repetition rate	78 kHz

Figure 1 shows the variation of the parameters of the electrons along the bunch as obtained from beam dynamic simulations [3]. While the energy spread and slice emittance are satisfactory, the variation of the peak current and the average energy of the electrons from different slices are significant. To understand the impacts of these variations to the cooling forces, we have conducted the PIC simulation with the code SPACE for each slice of the electrons.

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DESIGN OF A MICROBUNCHED ELECTRON COOLER ENERGY RECOVERY LINAC

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Abstract

Microbunched electron Cooling (MBEC), a type of Coherent electron Cooling (CeC), is a possible way to cool high energy protons; such an electron cooler can be driven by an energy recovery linac (ERL). The beam parameters of this design are based on cooling 275 and 100 GeV protons at the Electron-Ion Collider (EIC), requiring 150 and 55 MeV electrons, respectively. If implemented, a high energy cooler would serve to increase the average luminosity of the collider by mitigating the emittance growth caused by various processes. This ERL is designed to deliver a bunch charge of 1 nC, an average current of 100 mA, and strict requirements on the transverse emittance, slice energy spread, and longitudinal distribution profile. This paper covers the current state of the design.

INTRODUCTION

The Electron-Ion Collider (EIC) is a partnership project between Brookhaven National Laboratory (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). 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].

The present EIC baseline only includes cooling of the injected hadron beam prior to ramping. However, it is possible that a future upgrade to improve the luminosity will be desired, requiring the hadron bunches to be cooled during collision in order to maintain the beam emittance [2].

MICROBUNCHED ELECTRON COOLING

Coherent electron cooling (CeC) uses an electron bunch to encode the density variations of the proton bunch, 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 intrabeam 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.

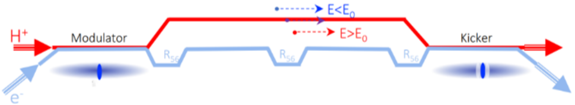

Figure 1: A representative layout of microbunched electron cooling. The protons and electrons co-propagate in the modulator section, separate into different lines, where the electron beam goes through a series of chicanes and drifts, before the electrons and protons once again co-propagate in the kicker section.

One type of coherent electron cooling is microbunched electron cooling (MBEC), the proposed mechanism for this ERL design to cool EIC protons during collisions. A representative diagram of this process is shown in Fig. 1. 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 [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 Fig. 2.

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OPTICS DESIGN FOR A STORAGE RING BASED ELECTRON COOLER FOR COOLING AT HIGH ENERGIES

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Abstract

The Ring Electron Cooler (REC) is an option to provide beam cooling for the Electron Ion Collider (EIC) at high energies. Based on a storage ring this machine can provide the beam current necessary for cooling at higher energies. While the electrons cool the ions the electrons are cooled by radiation cooling, which is enhanced using strong wiggler magnets. The ring has a race track shape, where one straight section is used for ion cooling and the other includes the wigglers with a peak field of 2.4 T. In our solution the sextupoles and octupoles necessary for chromaticity correction are also located in the wiggler section, where the dispersion function is optimized in the multipoles without increasing the emittances too much through radiation excitation and intra beam scattering. A constant dispersion in the cooling section allows redistributing cooling power from the longitudinal to the transverse direction. A dispersion-free section is inserted into the arcs for RF cavities and injection.

INTRODUCTION

The idea of using an electron storage ring for electron cooling is not new. It was proposed nearly 50 years ago by D. Cline et al. [1]. Here the ion beam is cooled by the electrons and the electrons are kept cool through radiation damping. Wiggler magnets are employed to increase the radiation.

A storage ring eliminates the need for a high current electron gun, which would be necessary for sufficient cooling of the EIC beams at top energy using a linac or ERL based cooler.

While in a linac the beam emittance is naturally low, in a ring cooler the emittance is determined by the equilibrium of the radiation damping and the heating from

- quantum excitation in dipoles.
- intra-beam scattering (IBS) everywhere where the dispersion is nonzero.
- beam-beam (BBS) scattering in the cooling section.

As IBS and BBS are functions of the emittance itself the program GETRAD [3] is used. GETRAD calculates the emittances iteratively, starting from a guess, using:

$$\epsilon_{\text{new}} = \frac{(\lambda_{\text{rad}} + \lambda_{\text{IBS}}(\epsilon_{\text{old}}) + \lambda_{\text{BBS}}(\epsilon_{\text{old}}))}{\lambda_{\text{damping}}}$$

where the lambdas are the heating and damping rates.

GEOMETRIC AND OPTICAL CONSTRAINTS

The bunch frequency of the ion ring is 98.6 MHz. It is preferable that each ion bunch is always cooled by the same electron bunch, i.e. the ratio of the harmonic numbers of ions and electrons is an integer. This requirement allows a ring length of 255 m, 426 m or 576 m. The length of 255 m does not allow the full use of the 176 m long straight section for cooling; 576 m has a too large space charge tune shift.

The 426 m circumference allows the wiggler section to be longer than the cooling section, resulting in a trapezoid shape as shown in Fig. 1.

Figure 2 zooms into the arc region. The straight section inside of each 180° arc are dispersion-free and are used for the RF cavities and the injection.

The REC uses redistribution of cooling from the longitudinal to the horizontal direction. This requires a 1 m dispersion in the cooling section.

EMITTANCE AND CHROMATICITY

The major contribution in each of the three heating mechanisms comes from the coupling of longitudinal scattering into the transverse direction, which is described by the H-function:

$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2 \quad \text{with} \quad \gamma = \frac{1+\alpha^2}{\beta}$$

The quantum excitation is exactly proportional to H, for IBS and BBS it is more complicated, but minimizing H is a recipe for a low emittance.

On the other hand we have to correct the chromaticity. For that purpose we need locations where the dispersion is large and the beta functions differ significantly. This requirement increases the H-function and leads to a larger emittance. The goal has to be to find a compromise between the two requirements and find suitable locations for the sextupoles.

The arcs are tiny compared to the rest of the machine. Placing the sextupoles in the arcs would concentrate them in two locations, which would harm the dynamic aperture. In the REC there is dispersion in the cooling section, but the beta functions are about equal, which does not allow effective chromaticity correction. The only place for sextupoles is therefore in the wiggler section.

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A NEUTRAL HYDROGEN MONITOR FOR ELECTRON COOLING STUDIES OF H^- IONS IN ELENA

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Abstract

H^- ions are routinely used for the recommissioning of the ELENA ring as well as for various machine studies. Because of the weak binding energy of the electron, these ions are stripped by the interaction with the residual gas molecules and the intense electron beam generated by the electron cooler after which they are lost on the vacuum chambers of the main machine dipoles.

A neutral hydrogen monitor is installed downstream from the electron cooling device in the extension of one of the dipole magnets and is used to study the above mentioned effects. This provides much information on the evolution of the beam size and position in the cooling section during the deceleration as well as the performance of the electron cooler.

INTRODUCTION

In ELENA [1,2] a dedicated linac, operating at an energy of 100 keV, allows the machine to be operated with H^- ions or protons when it is not sending antiprotons to the experiments. The proton mode of operation has never been used due to the complexity of changing the magnetic polarity of the ELENA ring resulting in a lengthy setting up. As the ELENA deceleration cycle lasts 15 seconds, up to seven "standard" cycles using H^- ions can be inserted between the antiproton cycles (repetition rate of 120 seconds) [3] in order to perform beam measurements and machine optimisation.

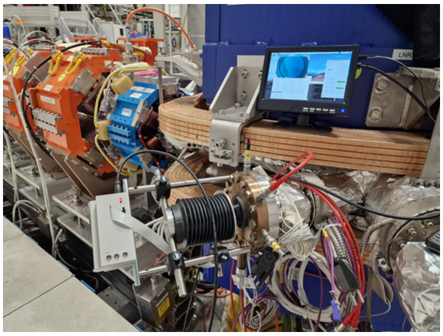

Figure 1: H0 monitor installation

HARDWARE

To measure the neutral hydrogen beam profile a detector (see Fig. 1), comprising of a chevron mounted microchannel plate (MCP) coupled to a P43 phosphor screen, is installed in the vacuum extension of the 60° bending magnet approximately 3.14 m downstream from the centre of the electron cooler. The H0 atoms that are created travel straight towards the monitor and as they hit the MCP surface, electrons are produced and are amplified in the MCP before they are accelerated onto the phosphor screen. The image of the phosphor screen is acquired by a Raspberry Pi4 computer [4] using the Pi HQ camera mount with interchangeable lenses.

SOFTWARE

The high voltage for the MCP and P43 screen is provided by an iSeg THQ dual channel power supply. A Python script controls the voltage ramp that is applied to the MCP and screen. Camera control is also performed via a Python script which enables the user to adjust the camera settings (resolution, exposure etc.) and to select the acquisition mode. Continuous, single/multi-frame and video capture are available and can be triggered synchronously with events in the ELENA magnetic cycle. Once the signals are acquired, offline programs enable the evaluation of the beam parameters as well as their evolution. One feature that was implemented was the possibility to selectively analyse regions of the video images. This was essential as multiple beam spots can be observed during the deceleration cycle (see Fig. 2) caused by the offset of the circulating beam inside the cooler with respect to the rest of the straight section.

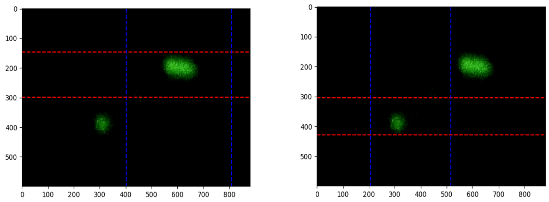

Figure 2: Signal cropping for selective analysis at 35 MeV/c

BEAM COOLING MEASUREMENTS

The alignment of the ion beam and the cooling electrons is essential in order to obtain the best cooling and hence reduce beam losses due to adiabatic blow-up and residual gas scattering. Beam position monitors can give information on the ion and electron beam trajectories but cannot give any indication on the efficiency of the cooling process. The effects of position and angle changes of the H^- beam on the cooling efficiency are directly observed on the H0 monitor and help to reduce the setting up time of the machine. The initial position and angle settings are shown on Table 1.

Position and Angle Scans at 35 MeV/c

At the first deceleration plateau of 35 MeV/c, a scan of the circulating beam trajectory and angle in the cooler section

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TRANSVERSE BBU SUPPRESSION WITH FEEDBACK FOR ENERGY RECOVERY LINACS

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Abstract

In this study, we present beam dynamics simulations of the Strong Hadron Cooling (SHC) Energy Recovery Linac (ERL) that incorporate a feedback (FB) system designed to mitigate Beam Breakup (BBU) instabilities. The FB effectively suppresses BBU and increases the threshold current by roughly an order of magnitude. Our analysis revealed the aliasing behavior of the dominant higher-order mode (HOM) and its suppression by the FB, as evident from the power spectral density (PSD) of the beam centroid's horizontal motion at the exit of the final linac section. Although the FB system— even when affected by noise—successfully reduced the BBU peak, it also amplified the PSD at other frequencies. These results provide important insights into BBU suppression and threshold current enhancement in ERLs.

INTRODUCTION

The Electron-Ion Collider (EIC) is a state-of-the-art, high-luminosity particle accelerator designed to collide highly polarized electrons with ions [1, 2]. To be constructed at Brookhaven National Laboratory (BNL) in collaboration with Thomas Jefferson National Accelerator Facility (JLab), the EIC originally planned to achieve its unprecedented luminosity through an innovative beam cooling technique known as Coherent electron Cooling (CeC) [3].

An Energy Recovery Linac (ERL) serves as the backbone of the CeC system, allowing the recovery of the electron beam's energy after cooling. This approach greatly improves energy efficiency, as the recovered energy minimizes the power deposited in the beam dump, thereby reducing both radiation concerns and the need for extensive cooling infrastructure. Detailed descriptions and design considerations of the ERL can be found in Refs. [4–6].

The general framework for ERL feedback (FB) systems has been discussed in Refs. [7, 8]. A schematic layout of the Strong Hadron Cooling (SHC) ERL incorporating an FB system is shown in Fig. 1. The injector accelerates the electron beam to 6 MeV before it enters the recirculating section of the ERL. The beam then passes sequentially through two single-cell 197 MHz cavities, two quarter-wave 591 MHz cavities, and another pair of 197 MHz cavities, reaching an energy of approximately 13 MeV. Subsequently, it traverses five 5-cell 591 MHz, four 5-cell 1773 MHz, and four additional 5-cell 591 MHz cavities, providing final energies of 55 MeV in Mode-B and 150 MeV in Mode-A operation. For detailed simulation studies of BBU effects in the EIC Cooler ERL, the reader is referred to Ref. [9].

HIGHER ORDER MODES

When the beam passes through the cavities, part of its wakefields are trapped inside long enough to impact the subsequent bunches in present and later passes. These trapped modes generated what is referred to as long-range wakefields, which have high Q-factors and act like narrow band resonator. The cutoff frequency is inversely related to the cavity iris size. Monopole modes produce longitudinal wakefields that may cause energy and timing fluctuations in the beam. However, their effect on beam instabilities is minor and can be mitigated by employing off-crest acceleration or deceleration. On the other hand, dipole modes generate transverse wakefields, which can deflect the beam and lead to transverse BBU (Beam Breakup) instabilities. This study specifically focuses on dipole HOMs (Higher Order Modes) and transverse BBU instability, as these are the dominant factors. For more details on the HOMs are given in Ref. [9].

FB SYSTEM SETUP

The feedback (FB) system consists of two BPMs located near the accelerating cavities (downstream of the laser heater) and four kickers positioned in the return line, as illustrated in Fig. 1. The kickers are placed such that the beam travels approximately 520 m (1.73 μs) downstream in the beamline between the BPMs and the kickers. As shown in Fig. 2, the kickers are positioned approximately 5–10 m apart, corresponding to a temporal separation of about 20–30 ns. This spacing provides sufficient latency within the FB loop for bunch-to-bunch correction.

The four kickers allow for independent correction of both beam angle and position in the horizontal and vertical planes. The feedback loops in each plane operate independently but can influence one another through transverse coupling between the planes. The coupling effects between the horizontal and vertical planes, resulting from magnet tilts and misalignment, are neglected. Similarly, delays in the feedback response are not considered in this initial analysis of the BBU feedback performance.

THRESHOLD CURRENT WITH FEEDBACK

The cavities used in these BBU tracking simulations are BNL-type cavities, and the corresponding HOM parameters are provided in Ref. [9]. A total of 30 dominant HOMs were included in the study—15 horizontal and 15 vertical modes. The threshold current without the feedback (FB) system is determined to be 229 mA, as shown in Fig. 3. At 230 mA, the HOM voltage grows exponentially, while at 229 mA, it remains stable and low.

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BEAM POSITION MONITORING FOR LOW ENERGY COOLING SECTION*

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Abstract

The Electron-Ion Collider is being constructed at Brookhaven National Laboratory. To achieve the required luminosity the hadron beam will be cooled at the injection energy to reduce its vertical emittance. This paper describes the beam position monitors for the cooling section.

INTRODUCTION

The Electron-Ion Collider (EIC) will employ Low Energy Cooler (LEC) dedicated to cooling proton bunches at injection energy ($\gamma\approx25$) [1,2]. LEC utilizes a 170 m long cooling section (CS), which is a straight section of the EIC hadron storage ring where electron and hadron bunches co-propagate. The 14 beam position monitors (BPM) installed in the CS should be capable to measure the positions of the electron and hadron independently. The hadron BPMs should measure beam position for the wide variety of bunch shapes as well. The signals from the pick-up electrodes will have large dynamic range due to the substantial variation of the bunch charges and length. The cable attenuation can also vary strongly.

The orbits of the hadron and electron beams should be transversely aligned to the accuracy better than 35 microns. The relative angular misalignments between the electron and proton trajectories in the CS must be kept below 15 microradians [3]. The mechanism for the measurement of the BPMs offsets between two BPM systems should be also developed.

BEAM PARAMETERS

The hadron beam parameters vary greatly from the Au^{+78} ions pilot bunch of 5 nC and bunch length of 4.2 ns to protons at store with 31 nC bunch charge and 200 ps bunch length. During ramp the proton bunch charge can be as great as 45 nC with same short length of 200 ps.

The cooling will happen at injection energy with relativistic factor of $\gamma=25.4$ (proton energy 23.8 GeV and electron energy 12.5 MeV). The proton beam during cooling will be stretched using harmonic RF cavity to the flat top of 3 ns. The profiles of the electron and proton beams are shown in Fig. 1.

The hadron BPM electronics should be able to handle signals from all set-ups. This will require thorough modelling of the analogue chain and digital processing.

The electron beam used for cooling will consist of the train of 24.625 MHz macrobunches, with each macrobunch containing three bunches separated by 5.1 ns (197 MHz RF system). Each electron bunch has a charge of 1.2 nC and r.m.s. length of 170 ps. Repeatable parameters of the beam make the design of the receivers easier.

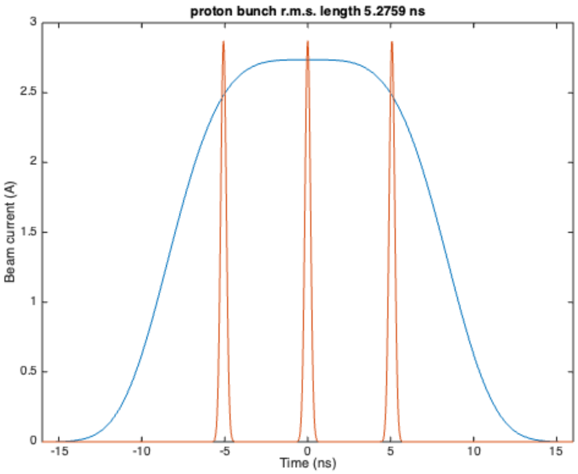

Figure 1: The profiles of the proton bunch (blue) and the electron beam (red). The r.m.s. proton bunch length is 5.3 ns.

SIGNAL PROCESSING

Conventional signal path includes a) cable connecting the pick-up electrode with BPM, b) RF front end conditioning the signal, eliminating the unwanted frequencies, and reducing the signal level to an acceptable level, c) controllable attenuator normalizing the signal and preventing overload, d) pre-amplifier, e) main filter providing the final frequency response of the analogue chain, f) the second amplifier compensating losses in the main filter, g) analogue-to-digital converter (ADC). ADC digitizes the signal and provides the stream of data for digital processing.

The electron beam generates 3 V peak signal on the 30 mm diameter button in the 127 mm diameter beampipe. The spectrum of the signal is shown in Fig. 2.

The weakest signal for the hadron BPM will be generated by a gold ion pilot bunch. Its amplitude at the button will be only 20 mV. The strongest signal is generated by the proton bunch of 45 nC during ramp when bunch length reaches 200 ps. The button signal will be on 70 V peak. The propagation of the signal through a cable reduces the amplitude to 40 V which still too high for the electronics. An RF front end with 3rd order low-pass filter of 150 MHz will reduce the amplitude to 3 V and can be further decreased by the attenuator (see Fig. 3).

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TIME DOMAIN STOCHASTIC COOLING SIMULATIONS: TRANSVERSE AND FILTER COOLING

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Abstract

Stochastic cooling is a technique for reducing the phase space volume of particle beams in accelerators improving the experimental conditions for facilities like the Antiproton Decelerator at CERN. We present a stochastic cooling simulation model, for the transverse and longitudinal planes. This work studies the cooling performance of particle beams under different scenarios, like different gains or number of particles, applying a feedback mechanism for the longitudinal plane called filter cooling. Some cases of emittance and momentum spread reduction are presented, as well as some interesting scenarios of unsuccessful cooling.

INTRODUCTION

Stochastic cooling [1–3] is applied to the beam in the CERN Antiproton Decelerator (AD) in both transverse and longitudinal planes during two plateaus, at 3.57 GeV/c and at 2.0 GeV/c. Specifically for the longitudinal phase space filter cooling [4, 5] using a notch filter is applied (Fig. 1).

The work presented in this paper, is a simplified time-domain simulation framework that models coasting beam stochastic cooling, for a smaller number of macro-particles. Both longitudinal and one transverse planes are included in this framework and filter cooling [3, 6] is applied in the longitudinal plane. Results are compared for different parameters, such as noise, gain and number of particles, illustrating scaling laws and the system's performance.

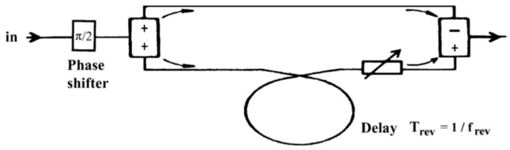

Figure 1: Diagram of a typical notch filter, consisting of a phase-shifter, a splitter, a short and a long transmission line and a “subtractor”.

MODELING APPROACH

One of the challenges for the modeling of coasting beam stochastic cooling is the seamless computation of correction to be applied at the kicker. The approach applied is to divide the macro-particles into two groups labeled *red* and *blue* and to track them alternately as sketched in Fig. 2. The (absolute) time increases from left to right. Particles within one group are described by the relative arrival time τ roughly within a time interval $\tau_H/2 \le \tau \le \tau_H/2$ with τ_H being half of the revolution time. The following steps are applied starting with particle coordinates at the position of the Pick-Ups (PU):

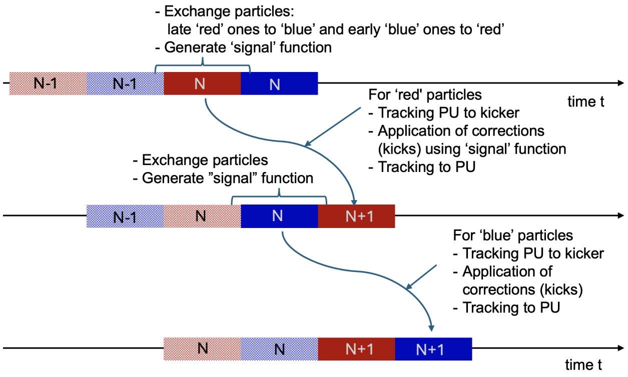

Figure 2: Alternate tracking of two groups of macro-particles. Iterations increase from the top to the bottom.

- To ensure that particles are within the relevant group and as first step of the procedure (see top of Fig. 2), particles of the red group with $\tau \ge \tau_H/2$ (blue group with $\tau \le -\tau_H/2$) are moved to the blue (red) group.
- Then “signal functions” describing the correction to be applied are computed for the “red” particles. The coordinates of all particles are available and are first binned in relative arrival time τ with a sufficient resolution. For the transverse plane, the sum of the positions is determined for each bin and used to compute the “signal function” at sufficient discrete times using a “response function” given in Eq. 1. The procedure for the longitudinal plane is similar with using the number of particles per bin instead of the sum of the positions and the requirement to use as well the “signal function” from a turn earlier for the implementation of filter cooling. The window, for which the “signal function” is computed extends from $-\tau_H/2 - \tau_{\mathrm{ovlap}}$ to $\tau_H/2 + \tau_{\mathrm{ovlap}}$ with τ_{ovlap} given in Eq. 2 to ensure that the correction to be applied can be computed for all macro-particles.
- The “red” particles are tracked to the position of the kicker by multiplication of the phase space vector with a transfer matrix determined from the Twiss parameters, the phase advances and the momentum compaction factor.
- The corrections from the stochastic cooling system are applied. Kicks applied are the product of a gain factor

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A CHARGE-AGNOSTIC DESIGN FOR 6D MUON IONIZATION COOLING

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Abstract

A muon collider presents a compelling path forward for high-energy physics, offering both energy reach and precision. The notable challenge in realizing the target luminosities for a muon collider is in the development of a sufficiently fast beam cooling scheme – one capable of several orders of magnitude in emittance reduction with minimal decay losses. Ionization cooling is the only proposed scheme to fit this criterion. Traditional ionization cooling channels are characterized by a solenoid-based lattice for beam focusing and a low-Z absorbing material wherein the beam deposits energy via ionization. Dipole fields are used to generate dispersion such that higher-momentum muons pass through more absorbing material, enabling 6D cooling by leveraging emittance exchange. The problem with this approach is the charge-specificity of the dispersion function, necessitating separate channels for μ^+ and μ^-. Here, the Helical FOFO Snake (HFOFO) is presented as an alternative approach to 6D cooling that can handle both signs of muon, enabling a single cooling channel.

INTRODUCTION

Confronted with myriad unsolved problems not addressed by the Standard Model, a muon collider presents an opportunity for both precision measurements and discovery potential at the 10 TeV scale [1]. However, the finite lifetime of the muon necessitates considerable R&D to make such a collider realizable. Notably, established cooling approaches are not fast enough for muons; ionization cooling, as demonstrated by MICE [2] and Muon g-2 [3], is a promising alternative.

The concept of ionization cooling is captured by

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0} \tag{1}$$

where ε_n is the normalized emittance, s is the path length, β is the velocity, E_μ is the energy of the muon beam, $\beta_\perp$ is the transverse beta value, m_μ is the mass of the muon, and X_0 is the radiation length of the absorbing material. The first term on the right describes cooling via ionization, while the second is a heating term due to multiple scattering.

To achieve ionization cooling in all six dimensions of phase space, the prescription is as follows: first leverage emittance exchange to (conservatively) increase the transverse emittance. Then induce dispersion via a dipole field to correlate position and momentum. Next pass the beam through a low-Z absorbing material in the shape of a wedge, facilitating momentum-dependent cooling, with higher-momentum particles passing through more material and hence losing more energy. Ionization deposition in the material acts as the nonconservative process required to shrink the momentum distribution. Longitudinal momentum can subsequently be restored via RF cavities.

The principal disadvantage of this approach is the requirement of a dipole field, which enforces the need for charge-specificity. To apply this scheme at a μ^+-μ^- collider, this implies two separate cooling channels are necessary, and charge separation must be performed immediately after the front-end [4]. However, considering the large initial phase space of the beam post-pion decay, charge separation at this stage will result in significant losses. Additionally, duplicate channels require increased construction costs. In this paper, we present an alternative: the Helical FOFO Snake (HFOFO), a charge-agnostic design to serve as an initial 6D cooling stage before charge separation. HFOFO was first proposed by Yuri Alexahin during the Muon Accelerator Program (MAP), but received little attention after the conclusion of the program [5]. Our recent efforts to revive and optimize the design will be detailed here.

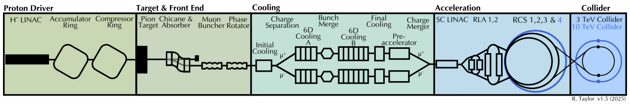

Figure 1: A proposed design for the muon collider accelerator complex, including HFOFO as the initial cooling section [4].

LATTICE DESIGN

The HFOFO lattice is composed of alternating-polarity, inclined solenoids for focusing and dispersion generation, as well as RF cavities and LiH wedge absorbers. The defining parameters of each of these elements are given in Table 1. One period in the lattice is defined as six focusing elements and the subsequent gaps, as depicted in Figure 2. The construction is such that the minima of the beta function align with the absorbers to maximize cooling. Nominally, the initial cooling channel would comprise 30 periods, plus a section at the start for matching, making for a total length of ~132 m. For a reference momentum of 221.8 MeV/c, as matched to the full channel ignoring stochastic effects, we would expect about 9% beam loss due to decays over this length.

Where HFOFO differs from standard ionization cooling channel designs is in the application of rotations about both the x- and z-axes, which we have defined by pitches and rolls, respectively. A constant x-rotation of 2.5 mrad is applied to every coil, inducing a dipole field and thereby dispersion.

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