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OPTICS FOR AN ELECTRON COOLER FOR THE EIC BASED ON AN ELECTRON STORAGE RING*

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Abstract

An electron cooler based on a storage ring is one of the options to improve the luminosity in the Electron-Ion Collider (EIC). The transverse emittance of the electrons in the cooler is driven by the quantum excitation in dipoles and wigglers, as well as by both beam-beam scattering with the ions and intra-beam scattering of the electrons in the regions with a non-zero dispersion. The resulting demand to minimize a dispersion conflicts with the need of a sufficient dispersion in sextupoles for chromaticity correction. In this report we discuss our studies of several approaches to electron ring lattice, including those typically used in light sources, and present resulting compromise between various requirements.

INTRODUCTION

The Electron-Ion Collider is being designed at the Brookhaven National Laboratory, with an anticipated start of construction in 2025. This machine will allow colliding 10 GeV electrons with 275 GeV protons. An important feature of this accelerator will be a luminosity of $10^{34}\text{cm}^{-2}\text{sec}^{-1}$. After injection the beam emittance of the ions, and therefore the luminosity, will degrade because of intra-beam scattering (IBS). In order to maintain a high integrated luminosity the ion beams must be cooled.

In the current design of the EIC Micro-bunched Electron Cooling (MBEC) [1] is selected as a promising new technique for cooling dense hadron beams. An alternative method is the traditional electron cooling, invented by Gersh Budker at INP, Novosibirsk, in 1966. Electron cooling has been tested in many applications and has been proven to work well with bunched beams in the LEReC cooler [2] at BNL. However, the EIC would be the first application with hadron energies greater than 10 GeV. The EIC operates at 100 GeV and 275 GeV.

The cooling rate of an electron cooler with bunched beams is proportional to:

$$\frac{1}{\tau} \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A m_p} \frac{1}{\gamma^2} \frac{N_e}{\epsilon_{xn}\epsilon_{yn}\sigma_z\sigma_\delta} \frac{L_{cs}}{C_{ring}} \tag{1}$$

where N_e is the number of electrons, L_{cs} is the length of the cooling section, C_{ring} is the ring circumference, Λ_c is the Coulomb log, $\epsilon_{xn}, \epsilon_{yn}$ are the normalized electron beam emittances, and γ is the Lorenz factor. The cooler becomes less effective with higher energies and we must increase the length and the electron current as well as maintain low emittances to achieve sufficient cooling rates.

The choices for the electron accelerator are a linac or a storage ring. When a photo-cathode is used in a linac the beam emittance is small, since each bunch is used only once for cooling the ions, but the electron current is limited by the life time of the cathode.

In a storage ring the beam current can be higher, but the emittance results from the equilibrium of heating of the beam by radiation excitation, intra-beam scattering of the electrons, heating by the ions (beam-beam scattering), and the radiation damping. It turns out that the IBS comprises a significant portion of the heating and strongly influences the design of the ring. Everywhere where the dispersion function is non-zero IBS couples the higher longitudinal temperature into the transverse direction and increases the emittance.

In an electron cooler the central velocity of the electrons and ions must be the same. With an ion energy of 275 GeV the required electron energy is only 150 Mev. As the radiated power is proportional to the 4th power of the energy it is therefore necessary to increase the radiation damping with wiggler magnets.

LAYOUT

The layout of the ring is shown in Fig. 1. It is shaped like a racetrack, with the cooling section being located in one straight section and the wigglers located in the other. Figure 2 shows the Twiss functions.

The arcs comprise only a small fraction of the circumference. It is not practical to concentrate the sextupoles for chromaticity correction in the arcs. We opted to eliminate the sextupoles from the arcs and use a tightly focused FODO lattice. Doing that allows keeping the dispersion small and minimizing IBS. We tried to use a double-bend-achromat lattice, but that did not decrease the beam emittance and increased the natural chromaticity significantly. The sextupoles are placed in the cooling section and the wiggler section.

In the cooling section the electrons overlay the ion bunch. It is 190 m long to maximize the interaction between electrons and ions. There are no magnetic focusing elements which results in large beta functions. An optical telescope reduces the beta functions at both ends to the small beta functions in the arcs. The non-zero dispersion in the cooling section allows redistributing longitudinal cooling into the horizontal direction [3]. It also allows placing sextupoles in the cooling section. However, since the phase advance over the whole cooling section is less than 90 degrees, placing many sextupoles would be detrimental to the dynamic aperture.

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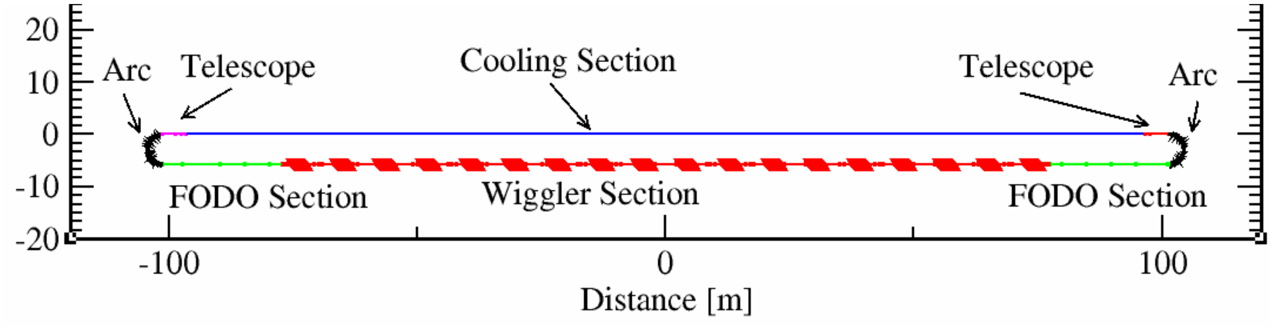

Figure 1: Layout of the ring cooler. The scale is the same in x and y. The arcs (black) have a diameter of 6 m. An optical telescope (red) connects the small beta functions in the arc to the large ones in the cooling section (blue). The other straight section has the wiggler section (red) with 18 vertical wigglers and 2 FODO sections (green) which allow setting the tunes and accommodate the RF and injection.

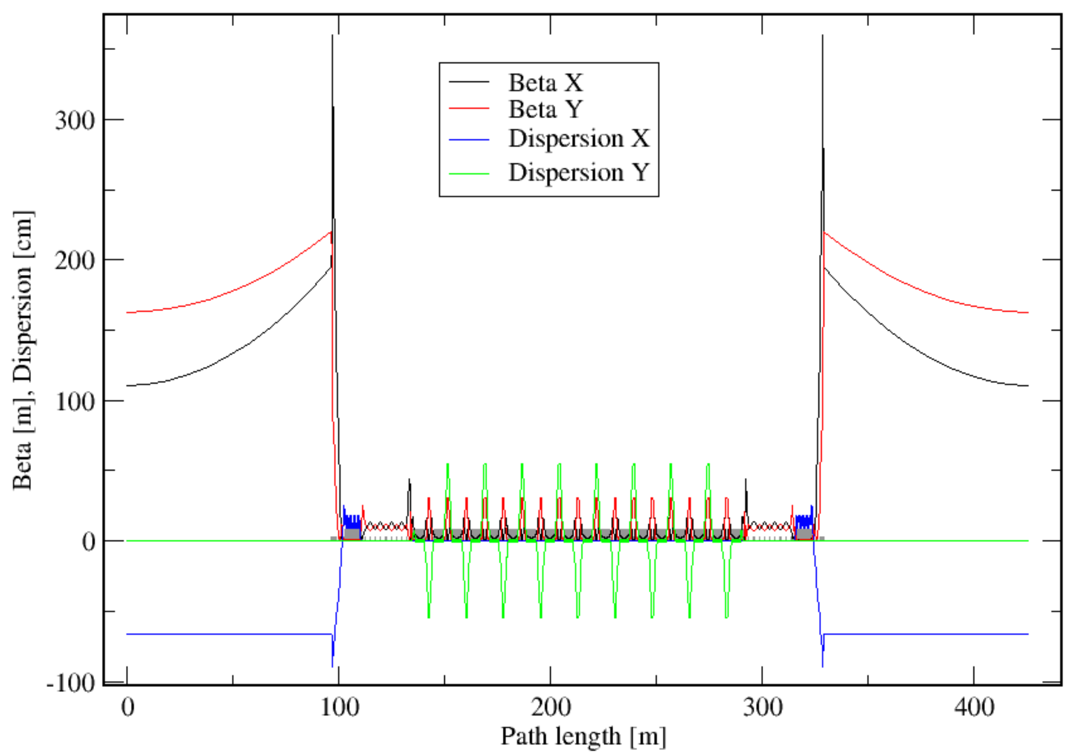

Figure 2: Optics function of the ring cooler, starting in the center of the cooling section.

The remaining location for the sextupoles is the wiggler section. We use 18 wigglers with a peak field of 2.4 T, which can be reached with Hybrid-Vanadium permanent magnets [4] . The gap is 2 cm and a wiggler period of 20 cm. Since the arcs and cooling section heats the beam in the horizontal direction and we want a round beam to cool the ions we use vertical wigglers.

The heating of the electrons from radiation excitation and (to a large degree) from IBS depends on the H-function:

$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2 \quad (2)$$

We use a gradient in the wigglers, so that they focus in the wiggler plane, so that the H-function in the wiggler is minimized.

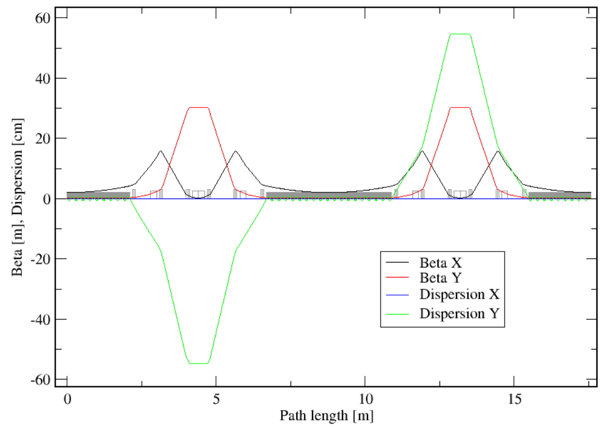

Figure 3: The optics between wigglers is similar to a DBA

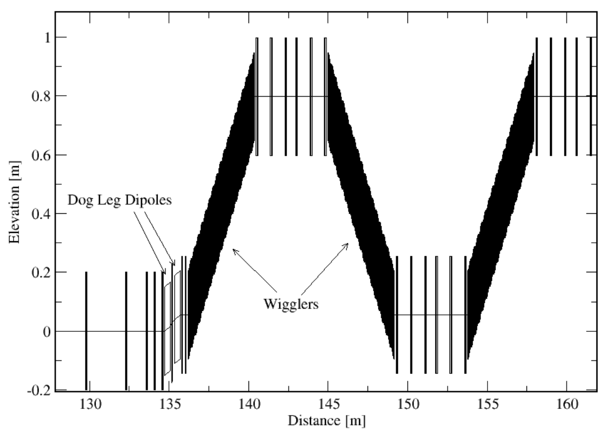

Figure 4: Side view of the wiggler section.

Since the H-function is constant outside dipoles it stays small between the wigglers and IBS is minimized. The optics between wigglers is similar to a DBA lattice(shown in Fig. 3), where the wigglers take the role of the dipoles. Unlike usual wigglers, which have half-strength poles at the ends to enter and exit on axis, we use full length poles and tilt the wiggler, as shown in Fig. 4. Using a dipole dog leg we create a vertical dispersion in front of the first wiggler. The dispersion exits with the same angle and is amplified to create a large dispersion between the wigglers, where the sextupoles are located.

In a previous design [5] we integrated a sextupole component into the wiggler field, so that the sextupoles are spread out over the whole length of the wigglers. Our new design has a factor of 2 and 3 lower emittances while taking advantage of cooling redistribution.

RESULTS

The emittances and cooling times are calculated with the GETRAD program. The program includes radiation excitation and damping and calculates the heating of the beam from IBS and from the cooling of the ion beam (Beam-beam scattering, BBS). Starting from initial emittances it iterates until equilibrium is reached. The cooling times of the ions is then calculated from the final emittances. The results can be seen in Table 1.

Table 1: Electron Cooler Emittances and Ion Cooling Times

Parameter	Value
ϵ_x	6.3 nm
ϵ_y	11.9 nm
σ_p	$1.23 \cdot 10^{-3}$
τ_x	147 min
τ_y	368 min
τ_p	210 min

The achieved cooling times are sufficient to prevent the degradation of the luminosity from intra-beam scattering of the ions.

By locating the sextupoles in the wiggler section we calculated a momentum aperture of 7 sigma, enough to operate the ring with frequent top-up injection.

CONCLUSION

An electron cooler based on a storage ring is an alternative to the Micro-bunched Electron Cooling. Such cooler is based on proven technologies and is capable of achieving sufficient cooling to combat intra-beam scattering in the ion beam.

We have developed a ring design which provides the required emittances and cooling times. We found a compromize between the need for small dispersion to minimize IBS and the need for larger dispersion for chromaticity correction.

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