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# REQUIREMENTS FOR EQUIPMENT IN COOLING SECTION OF EIC LOW ENERGY COOLER *

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*Abstract*

The Electron Ion Collider (EIC) requires an electron cooler operating at the EIC injection energy to obtain the design proton beam emittances. A non-magnetized RF-based electron cooler, the EIC Low Energy Cooler (LEC), is currently under design. It will be operating at γ-factor 25.4 and will be delivering 70 mA electron current to a 170 m long cooling section (CS). To obtain required cooling an input from electron-proton relative trajectory misalignment into an overall angle in the cooling section must be kept below 15 μrad. In this paper we give comprehensive consideration of the factors affecting the trajectory angles and set the resulting requirements to various CS subsystems.

## INTRODUCTION

The Electron Ion Collider (EIC) Low Energy Cooler (LEC) [1] is designed to pre-cool proton bunches at the injection energy ($\gamma = 25.4$) to $\varepsilon_{np} = 0.3$ μm of normalized vertical emittance.

The LEC is a non-magnetized, RF-based electron cooler. It utilises an approach to the cooling established by LEReC [2-5]. The LEC includes a 170 m long cooling section – a straight section of the Hadron Storage Ring where the overlapping bunches of protons and electrons co-travel with the same velocity.

The LEC electrons are produced in a DC gun by illuminating a photocathode with a high frequency laser. The electrons are accelerated to 13 MeV, transported to the cooling section and dumped after a single pass through the cooling section (CS).

The LEC layout is schematically shown in Fig. 1.

The exact formulas for the cooling rates in non-magnetized RF-based electron coolers are given in [6]. For the purpose of the following discussion, we give an approximate scaling relations between the rate and beam parameters:

$$\lambda \propto \frac{N_e L_{\mathrm{CS}}}{\left(\sigma_{\theta e}^2+\sigma_{\theta p}^2\right)\left(\sigma_{\perp e}^2+\sigma_{\perp p}^2\right)\sqrt{\sigma_{\delta e}^2+\sigma_{\delta p}^2}\sqrt{\sigma_{ze}^2+\sigma_{zp}^2}}, \tag{1}$$

where $N_e$ is number of electrons, $L_{\mathrm{CS}}$ is a length of the cooling section, $\sigma_{\theta e}$ and $\sigma_{\theta p}$ are respectively electron and proton bunches effective rms angular spreads, $\sigma_{\perp e}$ and $\sigma_{\perp p}$ are respective rms transverse sizes of the bunches, $\sigma_{\delta e}$ and $\sigma_{\delta p}$ are rms energy spreads, and $\sigma_{ze}$ and $\sigma_{zp}$ are rms lengths of the electron and proton bunches respectively.

To maximize the cooling rate while avoiding overcooling of the bunch core we require that the effective overall angular spread of electrons is $\sigma_{\theta e} \approx 25$ μrad, which is close to the protons angular spread in the CS.

The electron angles include the angles due to a "thermal" emittance $\sqrt{\frac{\varepsilon_{ne}}{\gamma \beta_{e\mathrm{CS}}}}$ (here $\beta_{e\mathrm{CS}}$ is electrons average $\beta$-function in the CS), angles ($\Theta_{\mathrm{SC}}$) driven by both the "self space charge" of the electron bunch and the proton-electron focusing in the CS [7], and average angle $\langle\theta\rangle$ caused by relative misalignment of electron and proton trajectories through the CS [8]:

$$\sigma_{\theta e}^2 = \frac{\varepsilon_{ne}}{\gamma \beta_{e\mathrm{CS}}} + \Theta_{SC}^2 + \langle\theta\rangle^2. \tag{2}$$

Assuming that the combined emittance and space charge driven angular spread is about 20 μrad, we can afford $\langle\theta\rangle = 15$ μrad of average misalignment of trajectories in the cooling section.

## LEC COOLING SECTION

The LEC cooling section consists of fourteen 12 m long modules. Each module contains a short solenoid combined with horizontal and vertical dipole correctors, a drift shielded by two layers of $\mu$-metal, and a BPM. Main parameters of the CS module are listed in Table 1.

Table 1: Design Parameters of CS Module

| Parameter | Value |
|---|---|
| Solenoid length [cm] | 18.9 |
| Maximum solenoid field [G] | 180 |
| Maximum corrector field [G] | 1.1 |
| Solenoid-BPM distance [m] | 12 |
| $\mu$-shielding attenuation | 1000 |

A schematic representation of the LEC cooling section can be seen in Fig. 1.

## TRAJECTORY ALIGNMENT

The electron trajectory through the cooling section will be defined by the CS proton trajectory. In the ideal case, one wants to have zero angle and displacement of electrons trajectory with respect to protons through the whole CS. In reality, there are multiple factors causing relative misalignment of electrons and protons. The electron beam trajectory can get misaligned with respect to the protons because of inclination or transverse displacement of a solenoid. A resulting trajectory angle and displacement at the solenoid's exit, cannot be ideally compensated by the dipole correctors.

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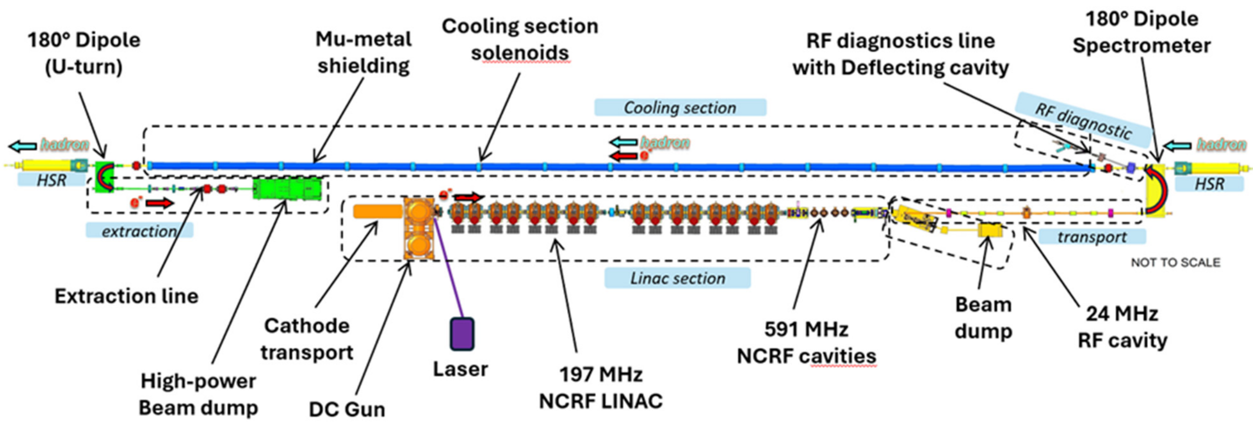



Figure 1: The LEC layout.

Since an expected attenuation factor from the CS magnetic shielding is around 1000, there is going to be a small dipole-like ambient transverse field in the solenoid to BPM drift, which also will contribute to average trajectory angles.

Additionally, in the cooling section the electrons are traveling in the focusing field created by the proton beam space charge. Therefore, as long as electron bunch centroid is transversely displaced with respect to the protons' trajectory, the electron trajectory will acquire an additional angle from the beam-beam kick [5, 9].

Finally, the CS BPMs can have errors, which will also inevitably result in misalignment of electron and proton trajectories.

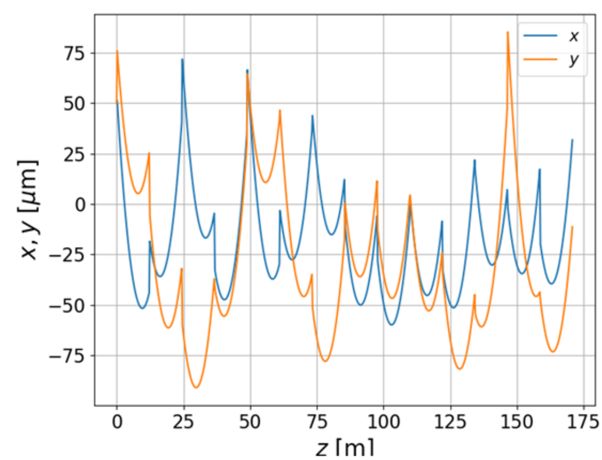
The detailed description and analysis of each individual misalignment factor is given in [8]. A mathematical model of cooling section was created [8] and used to study requirements to various CS subsystems. The model includes all the possible misalignment errors described above, as well as simulations of the beam alignment algorithm. For each parameter in the model having random errors, the errors are distributed uniformly within $[-A, A]$, where $A$ is the accuracy of the parameter's setting or reading.

Figure 2 shows an example of a resulting e-beam trajectory under an assumption of the CS solenoids being set with accuracy of 1 mm shift and 1 mrad angle, BPMs having 50 µm accuracy, and the ambient magnetic field being attenuated down to 1.5 mG. From obtained trajectory we calculate average angles in each drift and the trajectory angle averaged over the whole length of the CS (see Fig. 3).

Finally, we generate $N = 10^5$ cooling sections with random errors and repeat simulations for the each one, thus finding the probability distribution function $p(\langle\theta\rangle)$ of average total trajectory angle $\langle\theta\rangle$ in the CS for the given accuracies of setting various CS parameters. We define the probability of getting an average trajectory angle within limits $\langle\theta\rangle \in [\theta_0, \theta_1]$ as:

$$P = \frac{1}{N}\int_{\theta_0}^{\theta_1} p(\langle\theta\rangle)d\langle\theta\rangle \quad (3)$$

The results of such studies for the alignment accuracies outlined above are shown in Fig 4.



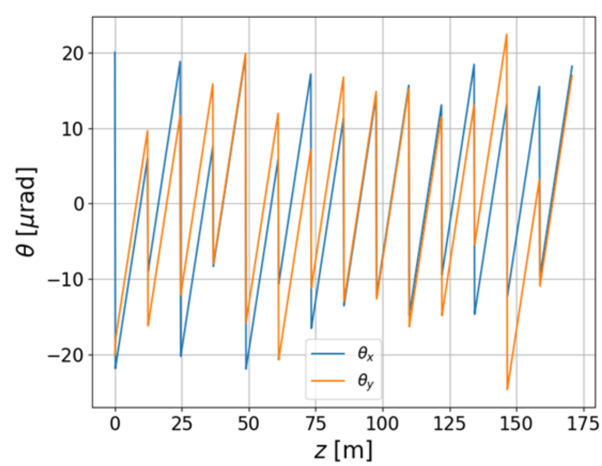




Figure 2: An example of e-beam trajectory and angles in the CS with respect to protons trajectory. The sharp changes in trajectory correspond to locations of solenoid-corrector modules.

From Fig. 4 we conclude that for the given accuracy of solenoids and BPM alignments in the presence of remnant ambient fields and proton-electron kick, the most probable trajectory misalignment angle is $\langle\theta\rangle \approx 12.6$ µrad, and the tale of the distribution reaches $\max(\langle\theta\rangle) \approx 14.2$ µrad.

The outlined technique allows us to explore dependence of distribution of trajectory angles on various parameters.

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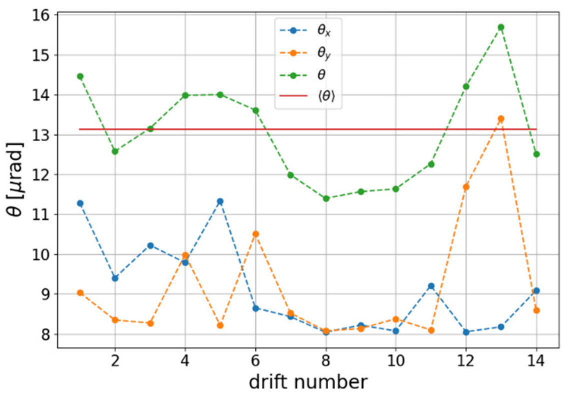


Figure 3: Average angles in the CS calculated for the trajectory shown in Fig. 2.

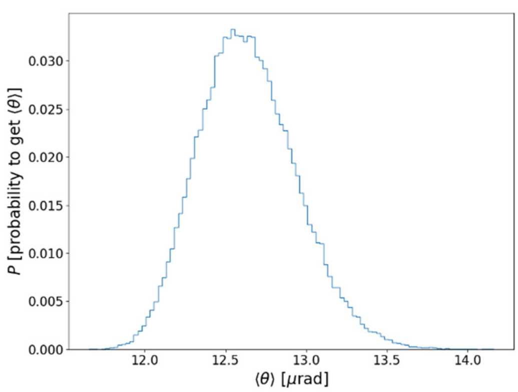


Figure 4: Probability of getting a particular trajectory misalignment angle in the CS.

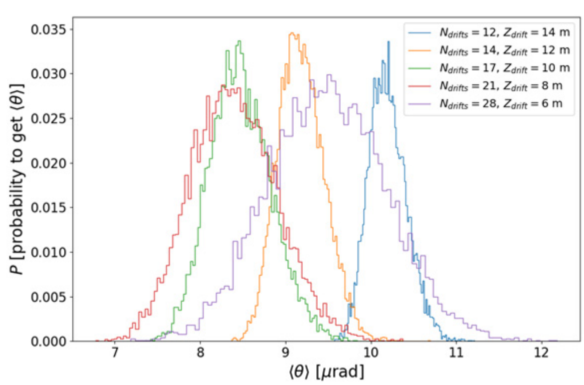


Figure 5: Distribution of misalignment probability depending on the length of solenoid-to-BPM drift.

For example, depending on how well the ambient field is attenuated, different drift lengths might become optimal. Changing drift length $Z_{\text{drift}}$ also changes number of drifts ($N_{\text{drift}}$) and number of BPMs and solenoids. Hence, the optimal drift length also depends on how accurate the BPMs' readings are and on how well the solenoids can be aligned.

In the following example we assume that the solenoids are set with accuracy of 1 mm shift and 1 mrad angle, BPMs having 35 μm accuracy, and the ambient magnetic field being attenuated down to 1 mG. The dependence of resulting probable misalignment distributions on drift lengths is shown in Fig. 5. Figure 6 summarizes the most probable and maximum expected misalignment angles.

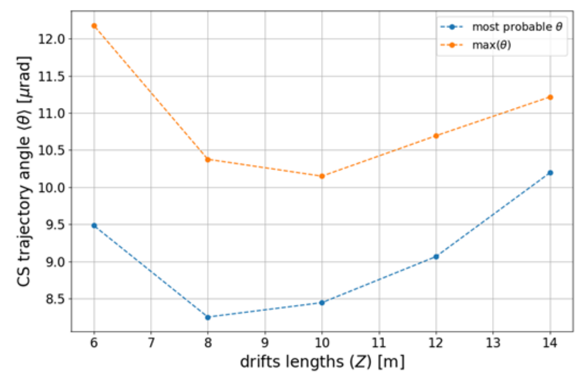


Figure 6: Most probable and maximum misalignment angle depending on the length of solenoid-to-BPM drift.

We performed the similar misalignment studies for various combinations of errors in the CS. Multiparametric optimization of settings of the CS parameters lead to the choice of requirements listed in Table 2.

Table 2: Requirements to LEC CS

| Parameter | Value |
|---|---|
| BPM error ($x$ or $y$) [μm] | <35 |
| Ambient magnetic field [mG] | <1 |
| Solenoid offset ($x$ or $y$) [mm] | <1 |
| Solenoid inclination ($x$ or $y$) [mrad] | <1 |

The resulting average relative angle between electron and proton trajectories for the tolerances listed in Table 2 is $\langle\theta\rangle < 11$ μrad. It satisfies the LEC requirements.

## CONCLUSION

The EIC Low Energy Cooler has a tight requirement of ~25 μrad for overall average angles of electrons in the LEC cooling section. The angular budget allows for no more than 15 μrad angles for the electron beam trajectory misalignments with respect to the CS proton trajectory.

The mathematical model of the LEC cooling section was developed and applied to statistical studies of trajectory alignment dependencies on various possible setting errors of the CS equipment. The model includes randomly distributed misalignments of the CS solenoids (shifts and inclinations), errors in BPMs readings, the remnant ambient magnetic field, and the proton-electron trajectory kick.

As the result of these studies, the realistic requirements to the CS equipment were derived (presented in Table 2). It was found that if the LEC CS satisfies these requirements, then the expected average trajectory misalignment angle will be ~11 μrad, which is well within the LEC angular budget.

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