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LATTICE DESIGN FOR LOW ENERGY COOLING IN EIC HSR-IR2*

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Abstract

Insertion Region at two o'clock (IR2) of the Relativistic Heavy Ion Collider will be modified to provide effective cooling for the Electron-Ion Collider (EIC). This paper summarizes the update of the HSR-IR2 lattice design to meet the evolving requirements of the EIC. The geometry has been redesigned to satisfy the yellow-to-yellow configuration. The injection optics is optimized to satisfy the Low Energy Cooling requirements and physical aperture.

INTRODUCTION

The EIC, under construction at Brookhaven National Laboratory, will collide polarized electron and hadron beams over a broad energy and species range. It targets a peak luminosity of 10^{34} cm^{-2}s^{-1} and average polarization of $\sim 70\,\%$ [1]. As shown in Fig. 1, the EIC includes multiple key components: the Hadron Storage Ring (HSR), the Electron Storage Ring (ESR), a new injector complex, and two interaction regions.

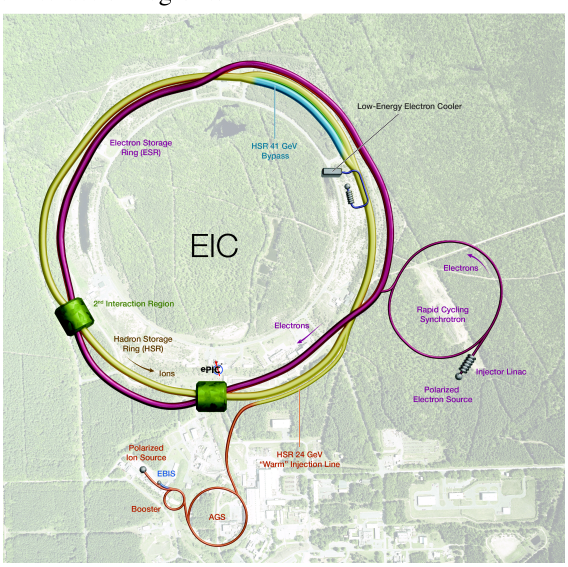

Figure 1: Conceptual layout of the EIC, showing key components including the HSR, ESR, injector complex, and interaction regions. IR2 serves as the cooling section for generating flat hadron beams and probably support high-energy cooling in future upgrades.

The HSR, upgraded from Relativistic Heavy Ion Collider (RHIC), will store highly polarized hadron beams with a flat profile, where vertical emittance ten times smaller than horizontal. Six helical Siberian Snakes [2] will preserve polarization during acceleration and storage. The Insertion Region at two o'clock (IR2) will serve as the cooling section to generate flat beams at injection energy and potentially provide high-energy cooling. It will also host one Siberian Snake.

This work serves as a follow-up study to our previously accepted paper [3], which investigated how to construct a smooth ramping path from the injection to top-energy optics. Since that study, the design requirements have evolved, necessitating rematching of the beam optics. In response to these changes, the current paper applies the methods developed in our previous work, providing updated results and insights that align with the revised specifications.

EIC COOLING STRATEGY AND CONSTRAINTS

The EIC leverages a flat hadron beam to maximize peak luminosity, with the vertical emittance an order of magnitude smaller than the horizontal. Unlike lepton machines, synchrotron radiation damping is negligible in the HSR due to the large rest mass. As a result, the hadron beam emittance is set by the ion source, which naturally produces round beams. External beam cooling is therefore essential to achieve the desired flatness. This concept has been experimentally demonstrated at RHIC using stochastic cooling techniques [4]. In the EIC, electron cooling will be applied at the injection energy to generate a flat beam, which will then be ramped to the top energy while preserving its emittance ratio.

To achieve optimal cooling performance, a long drift section is required in which electrons co-propagate with protons at the same velocity. During this interaction, both the Twiss and dispersion functions must be carefully controlled to ensure effective electron-hadron cooling. Detailed parameter table is shown in [3].

A major design change after April 2025 was to use electron cooling for gold beams as well, since stochastic cooling cannot achieve the target emittance ratio in a short time. Due to gold's lower charge-to-mass ratio, its injection energy is approximately 2.4 times lower than that of protons, resulting in a larger geometric emittance at injection. This poses a more stringent challenge: the Twiss parameters required for efficient electron cooling are now in tension with the injection aperture constraints, which demand physical aperture to accommodate 7σ horizontally and 6σ vertically.

As a result, a warm doublet is inserted at both sides of the long drift to provide flexibility to control beam sizes at injection energy, as shown in Fig. 2.

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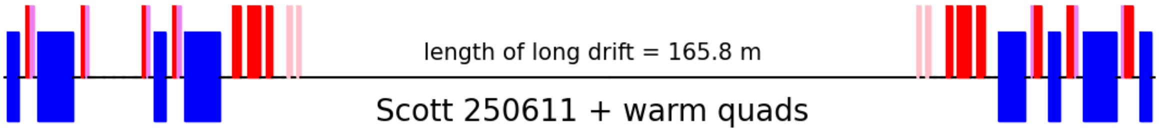

Figure 2: HSR-IR2 layout optimized to maximize the drift length for low-energy cooling. Blue, red, violet, and pink blocks represent RHIC dipoles, major quadrupoles, trim quadrupoles, and newly added warm quadrupoles, respectively. All quadrupoles are used as tuning knobs for beam optics matching.

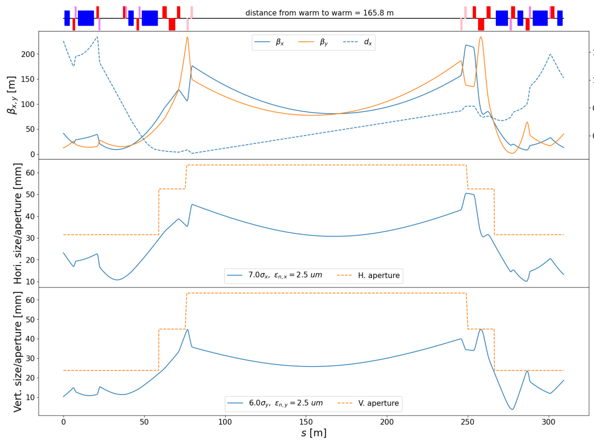

Figure 3: IR2 injection optics with increasing s clockwise. The beam direction is from right to left. Top: Beta and dispersion functions. Middle and bottom: Horizontal beam size of 7σ and vertical beam size of 6σ, both with a normalized emittance of $\epsilon_x = 2.5\,\mu\mathrm{m}$.

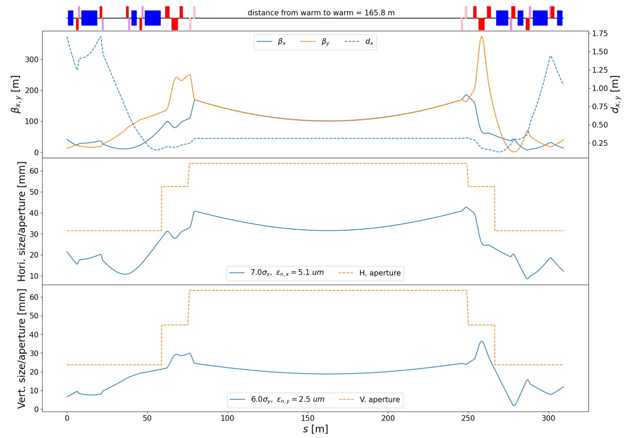

Figure 4: IR2 optics for low-energy cooling. The beam direction is from right to left. Top: Beta and dispersion functions. Middle: Horizontal beam size (7σ) with normalized emittance $\epsilon_x = 5.1\,\mu\mathrm{m}$. Bottom: Vertical beam size (6σ) with normalized emittance $\epsilon_y = 2.5\,\mu\mathrm{m}$. In the middle and bottom plots, dashed lines indicate the physical aperture.

MATCHED SOLUTIONS

Figure 3 shows the matched beam optics at the injection energy of 9.8 GeV per nucleon. Since no cooling is applied at this stage, the only constraint is the aperture requirement. The symmetry conditions $\alpha'_{x,y} = 0$ and $\eta'_x = 0$ at the center of the long drift are relaxed to increase flexibility in matching.

Each major quadrupole is powered independently from its adjacent trim quadrupole. Most major-trim pairs are configured with opposite polarities, enabling the formation of local doublets that control both horizontal and vertical beam sizes. However, because the major and trim quadrupoles are located in close proximity, a side effect is that both magnets must operate at relatively high strengths to produce the desired net focusing, which bring difficulties to find solutions at higher energies.

Figure 4 show the IR2 optics for low-energy cooling at 24 GeV per nucleon. The symmetry conditions $\alpha'_{x,y} = 0$ and $\eta'_x = 0$ are enforced. The beta and dispersion functions are well controlled to meet electron cooling requirements. Considering the strong intra-beam scattering at low energies and the ramping impact, the horizontal emittance is assumed to be doubled at cooling energy.

Figure 4 presents the IR2 beam optics optimized for low-energy cooling at 24 GeV per nucleon. In this case, the symmetry conditions $\alpha'_{x,y} = 0$ and $\eta'_x = 0$ are strictly enforced at the center of the long drift. The beta and dispersion functions are carefully matched to meet the cooling requirements.

Given the strong intra-beam scattering (IBS) at low energies and the potential impact of beam ramping, the horizontal emittance is assumed to double relative to its injection value. Specifically, a normalized horizontal emittance of $\epsilon_x = 5.1\,\mu\mathrm{m}$ is used in the constraints, while the vertical emittance remains at $\epsilon_y = 2.5\,\mu\mathrm{m}$. The beam sizes corresponding to 7σ in the horizontal and 6σ in the vertical directions are plotted alongside the physical aperture for comparison.

Figure 5 shows the IR2 beam optics configured for top-energy operation. In this setting, all trim and warm quadrupoles are turned off, as their strengths are weak and have small impact at high energy. The lattice is optimized to accommodate the fully ramped beam while maintaining sufficient aperture margins.

RAMPING CURVES

To ensure a smooth transition from injection to top-energy optics, the intermediate-penalty method described in [3] is applied. The resulting ramping curves for various magnet families are shown in Fig. 6. The transfer functions are 14.983 T/(m · kA) for major quadrupoles, 9.546 T/(m · kA) for major triplets, and 0.283 T/(m · A) for trim quadrupoles.

The ramping profiles are continuous across the full energy range, from injection to top energy. However, their first derivatives exhibit discontinuities at the cooling energy. This is because linear interpolation is used independently between the injection and cooling configurations, and be-

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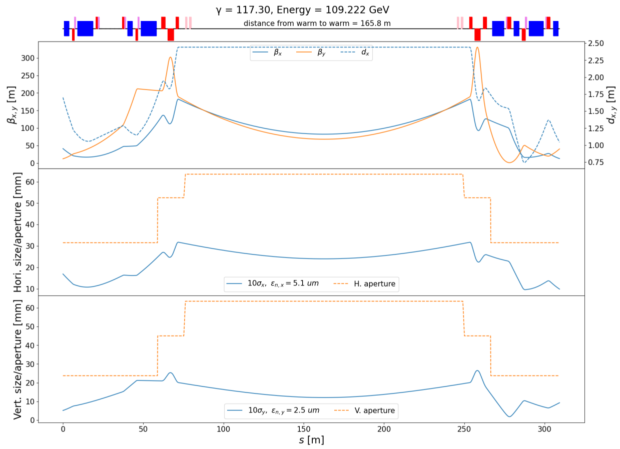

Figure 5: IR2 optics for top-energy operation. The beam direction is from right to left. Top: Beta and dispersion functions. Middle: Horizontal beam size of 10σ with normalized emittance of $\epsilon_x = 5.1\,\mu\text{m}$. Bottom: Vertical beam size of 10σ with normalized emittance of $\epsilon_y = 2.5\,\mu\text{m}$. In middle and bottom plots, the dashed lines show the physical aperture.

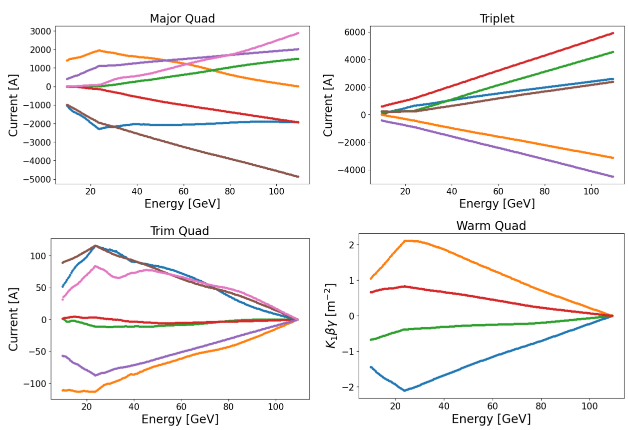

Figure 6: Ramping curves for major arc quadrupoles, major triplets, trim quadrupoles, and warm quadrupoles. The transfer function of the warm quadrupole is unknown, so the vertical axis in the last plot represents $K_1\beta\gamma$ instead of magnet current.

tween the cooling and top-energy configurations, resulting in a deflection at the cooling energy.

CONCLUSION

This paper presents an updated IR2 lattice design to support low-energy electron cooling and top-energy operation in the Electron-Ion Collider. Compared to earlier configurations, the new design accommodates the more stringent aperture requirements arising from the decision to cool gold beams, which have lower injection energy and larger geometric emittance. Matched optics solutions are provided for injection, cooling, and top-energy stages, with attention to Twiss and dispersion control in the cooling region. A continuous ramping path is constructed using an intermediate-penalty method, ensuring feasible quadrupole settings across the full energy range. These results form the basis for further refinement of the HSR-IR2 design.

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