# OPTIMIZATION OF CHROMATICITY COMPENSATION AND DYNAMIC APERTURE IN MEIC COLLIDER RINGS*

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## Abstract

The conceptual design of the Medium-energy Electron-Ion Collider (MEIC) at Jefferson Lab relies on an ultra-small beta-star to achieve high luminosities of up to $10^{34}$ $cm^{-2}s^{-1}$. A low-beta insertion for interaction regions unavoidably induces large chromatic effects that demand a proper compensation. The present approach of chromatic compensation in the MEIC collider rings is based on a local correction scheme using two symmetric chromatic compensation blocks that includes families of sextupoles, and are placed in a beam extension area on both sides of a collision point. It can simultaneously compensate the first order chromaticity and chromatic beam smear at the IP without inducing significant second order aberrations. In this paper, we investigate both the momentum acceptance and dynamic aperture in the MEIC ion collider ring by considering the aberration effects up to the third order, such as amplitude dependent tune shift. We also explore the compensation of the third order effects by introducing families of octupoles in the extended beam area.

## INTRODUCTION

The high luminosity pursued in the nuclear physics programs requires an intensively strong focusing at the Interaction Point (IP) in an electron-ion collider [1,2]. A large transverse beam extension is inescapable before the beam is tightly focused by the Final Focusing Block (FFB). This leads to large chromaticity and chromatic beam smear at the IP. A new concept for an achromatic low-beta interaction region (IR) design has been developed to compensate chromatic effects by using a Chromaticity Compensation Block (CCB) [3]. In this design approach, the number of aberration conditions at IP is greatly reduced by requiring certain symmetries of the beam orbit motion and of the dispersion and by utilizing a symmetric arrangement of quadrupoles, sextupoles, and/or octupoles in the CCB. Such a scheme allows simultaneous compensation of the 1st-order chromaticities and chromatic beam smear at the IP without inducing significant 2nd-order aberrations

A schematic of generic IR design is shown in Fig. 1. The Beam Extension Section (BES) first expands the beam from the arc to the size required for final focusing. The beam next passes through the CCB, which creates an angle spread negatively correlated with the chromatic kick

of the FFB, so that FFB's chromatic effect is cancelled. Then the FFB focuses the beam to the required spot size at the IP.
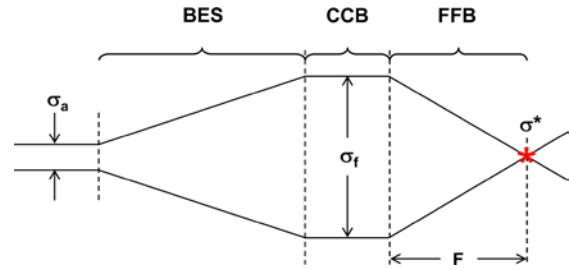


Figure 1: Schematic of the IR design consisting of the BES, CCB and FFB.

The implementation of a complete IR optics in the MEIC ion collider ring is shown in Fig. 2. The CCB is composed of eight symmetrically-arranged alternating bends with seven quadrupoles placed symmetrically between them. The quadrupole strengths are adjusted to produce a total CCB transfer matrix that meets the symmetry requirements. Note that the CCB bends on the opposite sides of the IP are reversed making the dispersion anti-symmetric with respect to the IP. This is done for the purpose of electron and ion IR footprint matching.
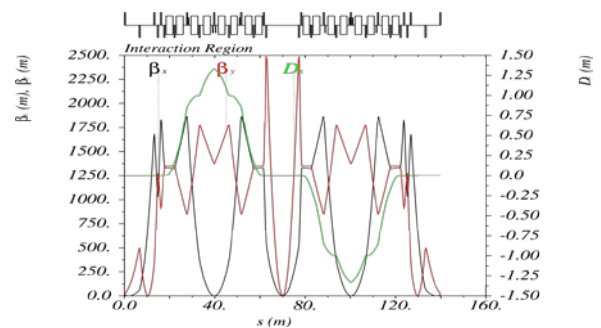


Figure 2: Optics of a complete IR in the MEIC ion ring.

## CHROMATICITY COMPENSATION

In conformity with the chromaticity compensation concept discussed above, two sextupole pairs are inserted in each CCB. The sextupoles in each pair are identical and are placed symmetrically with respect to the center of the CCB. Placement of sextupoles is shown by the shorter bars in Fig. 2. The sextupole positions are chosen at the

points where the dispersion is near maximum and there is a large difference between the horizontal and vertical beta functions. The two parameters corresponding to the strengths of the sextupole pairs are adjusted to compensate the horizontal and vertical linear chromaticities.
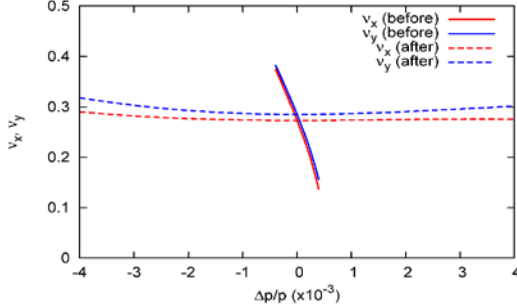


Figure 3: Chromatic dependence of the fractional betatron tunes before and after chromaticity compensation.

For the present MEIC ion ring design, the horizontal and vertical chromaticity values are -278 and -268, respectively, before the linear chromaticity compensation. Two sextupole families are used to adjust the slopes of the chromatic horizontal and vertical betatron tune curves to zero. The chromatic tune dependence before and after the compensation is shown in Fig. 3. The horizontal (vertical) tune variation is less than 0.005 (0.01) and 0.02 (0.03) within $\Delta p/p$ of about ±0.2% and ±0.4%, respectively.

## MOMENTUM ACCEPTANCE

An effective method to demonstrate the momentum acceptance and nonlinearity is the frequency map from particle tracking, as given in Fig. 4. At the 60 GeV/c design beam energy of the MEIC ion ring, the maximum horizontal rms beam size is 3.2 mm due to the large 7 m detector space, and the vertical rms beam size is 1.6 mm, which makes it challenging to obtain a large horizontal dynamic aperture. Therefore, the frequency map is computed in the ($x$-$\Delta p/p$) space from tracking particles for 2000 turns in a well-established accelerator simulation software called *Elegant* [4] and plotted in Fig. 5. The color reflects the tune change in terms of the tune diffusion defined as $d = \log(\Delta \nu_x^2 + \Delta \nu_y^2)$ where $\Delta \nu_{x,y}$ is the tune change from the first to second half of the simulation in the horizontal and vertical planes, respectively. The diffusion index is an excellent criterion for long term stability and enables us to see the nonlinear behaviour. The more negative the diffusion, the smaller the nonlinear effects are.

Two conclusions can be drawn immediately from the frequency map in Fig. 4:

1. the momentum acceptance can easily reach $\Delta p/p$ of ±0.4% with only linear chromaticity compensation,
2. the uniform distribution of color means that there are no strong resonant perturbations in the particle tracking.

The simulation was terminated at $\Delta p/p = \pm 0.4\%$, which is $\sim 14\sigma_\delta$ ($\sigma_\delta$ is the RMS momentum spread of about 0.03%, which is expected after cooling) and is conventionally considered to be sufficient to demonstrate an adequate momentum acceptance. Thus, without any further compensation of the $2^{nd}$ order chromaticities, the chromaticity compensation concept has resulted in an excellent momentum acceptance.
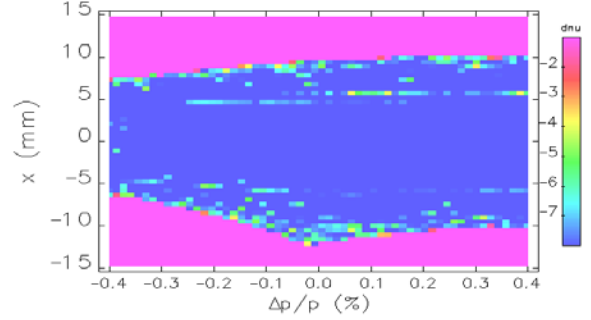


Figure 4: Frequency map in the (x-Δp/p) space. The color reflects the tune change in terms of the tune diffusion defined as $d = log(\Delta \nu_x^2 + \Delta \nu_y^2)$.

Figure 5 is the tune footprint corresponding to the particle tracking used for the calculation of the frequency map in Fig. 4. As in the frequency map, the color for the tune footprint reflects the tune change in terms of the diffusion index. The lines stand for the betatron resonances up to $3^{rd}$ order; higher-order resonances are not shown in this plot. Since the frequency map is calculated for particles with initial coordinates in (*x-Δp/p*) space, the vertical tune variation arises only from the chromatic tune dependence, which is around 0.03 within $\Delta p/p$ of ±0.4% as shown in Fig. 3. The horizontal tune variation is about 0.14, which is significantly larger than the chromatic tune change of 0.02 corresponding to $\Delta p/p$ of ±0.4% in Fig. 3. This indicates that, after the chromaticity compensation, the horizontal betatron motion produces a substantial tune change, which can drive the particles close to or into a resonance mode and cause particle loss. The tune footprint can instantly reveal the movement of the particle tunes, which allows us to understand the tune trend due to particle motion and/or adjust the design tunes to avoid approaching or crossing some strong resonances.
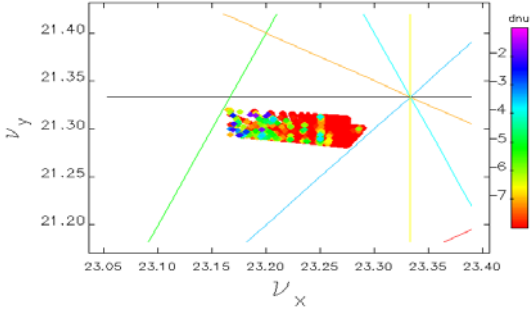
Figure 5: Tune footprint. The color reflects the tune change in terms of the tune diffusion defined in Fig. 4.

## DYNAMIC APERTURE

By using the symmetric CCB scheme for the chromaticity compensation, the dynamic aperture in the transverse directions of the MEIC ion ring is explored by tracking particles for 1000 turns with increasing initial horizontal (x) and vertical (y) amplitudes until the boundary between survival and loss is found as illustrated in Fig. 6 by the red line. The dynamic aperture for the on-momentum particle at the entrance into the final focusing block can reach ~10 mm (~$4\sigma_x$) horizontally and 18 mm (~$15\sigma_y$) vertically. Simulations show that the particles having large initial amplitudes experience stronger non-linear fields in the sextupoles, resulting in the third-order aberration: amplitude dependent tune shift.

As seen from the upper two plots in Fig. 7, the horizontal and vertical tunes change from the design values by 0.08 (red line in the left plot) and 0.04 (blue line in the right plot), respectively, within the amplitude range of about ±10 mm. A straightforward approach to compensate the amplitude-dependent tune shift caused by the sextupoles is to introduce octupoles. Since the momentum acceptance is large enough after the chromatic correction using the CCB's, families of octupoles are placed in dispersion-free regions, leaving the chromatic correction unaffected. Besides, to reduce the octupole strengths, they should be placed at large beta-function points. After the compensation of the 1st order amplitude dependent tune shifts $dv_{x,y}/ dJ_{x,y}$, the horizontal and vertical tune changes are now 0.04 and 0.03, respectively, within the amplitude range of over ±15 mm, as given in the lower two plots in Fig. 7, and the dynamic aperture is increased as shown by the blue line in Fig. 6, compared to the red line without the compensation of the 1st order amplitude-dependent tune shift.
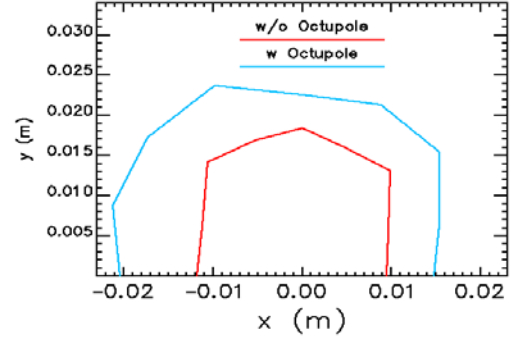


Figure 6: Dynamic aperture in the (y-x) space for the MEIC ion ring without (red) and with (blue) octupole minimization of the 1st order amplitude dependent tune shift.
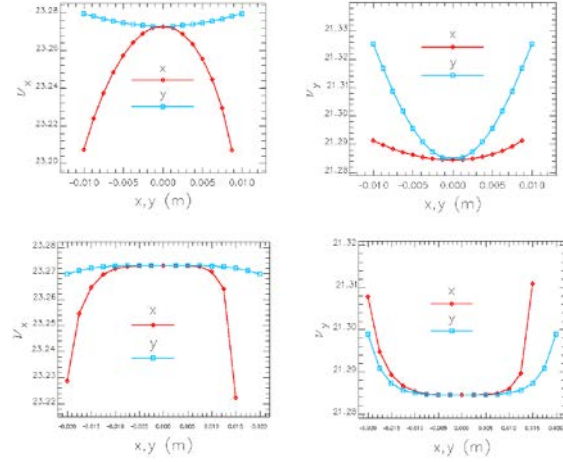


Figure 7: The horizontal (left) and vertical (right) tune variation as a function of initial transverse amplitudes $x$ and $y$ before (upper) and after (lower) minimizing the 1st order amplitude dependent tune shift.

## CONCLUSION

A new symmetry-based Chromaticity Compensation Block (CCB) design concept in the MEIC collider interaction region allows simultaneous compensation of the 1st-order chromaticities and chromatic beam smear at the IP without inducing significant 2nd-order aberrations. This approach results in an excellent momentum acceptance. The dynamic aperture after the chromaticity correction is reasonably large with the compensation of the 1st-order amplitude dependent tune shift using octupole families, and further optimization may be needed depending on the specific requirements. Evaluation of the impact of errors is under progress.

## ACKNOWLEDGEMENTS

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