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DYNAMIC APERTURE CORRECTION FOR RING ELECTRON COOLER*

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Abstract

The Ring Electron Cooler is one option to provide cooling to the Electron Ion Collider's 275 GeV proton bunches. Using traditional electron cooling this racetrack shaped storage ring uses one straight section to cool the protons and the other one to enhance the radiation damping of the electrons using 2.4 T wigglers. These sections comprise the majority of the ring and are connected by short arcs. Space for sextupoles and octupoles is made in short straight sections between the wigglers. The strong wigglers and limited space for correction magnets create challenges in finding a suitable dynamic aperture correction. In this paper, we outline the challenges present in rings of this type and present a correction scheme that meets the aperture requirements of the design.

INTRODUCTION

The Ring Electron Cooler (REC), is under design as a possible solution to the cooling need for the Electron Ion Collider's (EIC) Hadron Storage Ring (HSR) at its top energy of 275GeV.

In order to counteract emittance growth in the HSR, the REC design uses electron cooling [1] with a multi-turn ring. The electron bunches will be reused for cooling on many turns. To counteract the growth of electrons emittance and energy spread, caused by intra-beam scattering (IBS) and proton-electron beam-beam scattering, substantial radiation damping is needed. The cooling of electrons through radiation damping is facilitated by dedicated wigglers, with the parameters important for cooling and dynamic aperture shown in Table 1.

The wiggler section contains 18 wigglers alternating with short sections housing quadrupoles and sextupoles. These are arranged in 17 alternating wiggler blocks. Each of these wigglers have a 2.4T main field and are 4.2m long, and are responsible for the majority of the electron damping [2].

Another consideration in a ring based cooler is the need to maintain a dynamic aperture sufficient to obtain the beam lifetime needed for the desired cooling. This was determined to lead to a requirement of 5σ for the transverse and momentum apertures.

LATTICE OVERVIEW

The lattice has the approximate layout of a short and long trapezoid, with the cooling section on the top which overlaps with the HSR, and the bottom housing the wiggler section. The two short straight sections on the sides are to be used for injection and RF systems. Short arcs connect the sides as shown in Fig. 1.

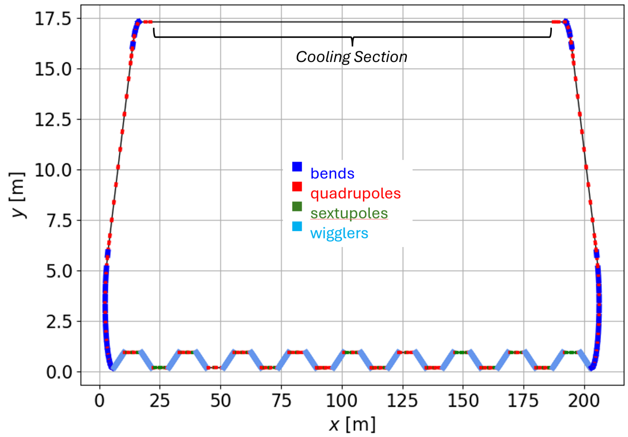

Figure 1: REC layout.

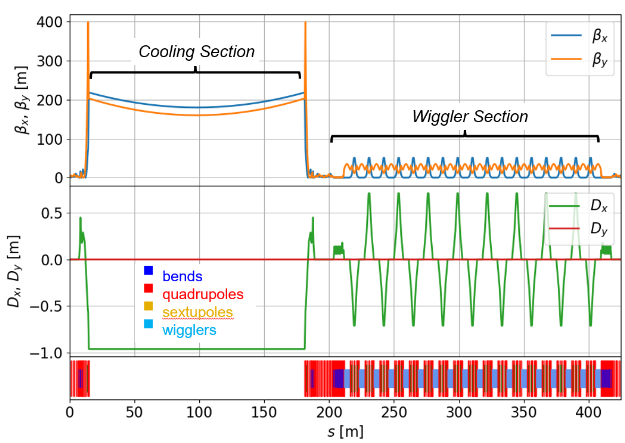

Figure 2: REC optics and lattice.

In order to reduce emittance growth due to IBS, the optics in the wigglers are desired to minimize the function:

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2. \quad (1)$$

Inside the wigglers, the periodic dispersion is small, leading to the first term in $\mathcal{H}_x$ to have small contribution. The derivative of dispersion (η_x') is large in the wigglers, leading to the need to reduce β_x. This is accomplished by adding horizontal focusing in the wigglers, resulting in the optics in Fig. 2.

There are multiple choices of wiggler fields that can achieve similar focusing, however the non-linear effects of these fields on dynamic aperture can vary significantly. The conceptually simplest choice of fields is a wiggler with a superimposed quadrupole field. Unfortunately, this field configuration was shown to cause large chromaticity for the

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Table 1: Baseline Parameters

N_e	$1.3{\cdot}10^{11}$
Relativistic γ	293
Total length [m]	426
Cooling section length [m]	170
Cooling section η_x [cm]	100
Cooling section $\beta^*_{x,y}$ [m]	180, 160
Number of wigglers	18
Wiggler length [m]	4.2
Wiggler field [T]	2.4
Main RF frequency [MHz]	98.4
Main RF voltage [kV]	50
2^{nd} harmonic voltage [kV]	25
Emittance (x,y) [nm]	7.8, 7.8
Fractional tune (x,y)	0.13, 0.35
Space charge tune shift (x,y)	0.14, 0.14

needed focusing, leading to large sextupole strengths and poor dynamic aperture [3]. These fields were further shown via an analytic approximation to have a singularity in the linear chromaticity in the region of the required focusing [4]. An alternative ”sextupole” like field is used in place of the superimposed quadrupole, yielding chromaticity results similar to the bare wiggler.

PHASE CHANGE IN WIGGLER SECTION

The sextupoles are located in short straight sections between wigglers. As the two element types are responsible for strong non-linear transverse effects, choosing a proper phase advance across wiggler blocks can enable partial cancellation and improve DA.

In order to determine the ideal phase advance, phase trombones were inserted into the middle of the wigglers and varied for many DA calculations. Three regions of potential phase advances were tried, with region two in Fig. 3 being chosen. This was due to the strong results for dynamic aperture, but having a better optics solution than region one.

Optics matching was achieved by varying quadrupole strengths between wigglers and altering wiggler parameters. This match resulted in similar optics in the wiggler section, except that peak vertical β-function increased approximately 20% (Fig. 4).

TUNE OPTIMIZATION

The general range for the working point for the tune was chosen in order to have coupling from the space charge tune shift and was the primary concern for the tune placement. In this region, working points were tested for effect on the dynamic aperture.

As transverse aperture is controlled well by phase advances in the wiggler blocks, the tune was chosen to maximize momentum aperture. A band of tunes good for momentum aperture was found (see Fig. 5) and the middle of the band was chosen as the working point for this study. This band offers an additional advantage of having a large range

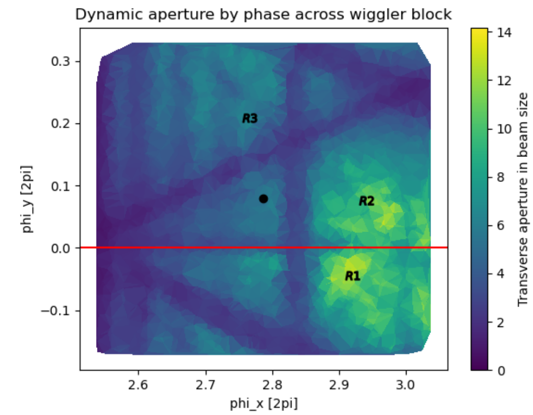

Figure 3: Transverse DA by phase across wiggler block. Achieved by phase trombone matrices. Black dot shows starting phase advance. Three potential phase advance choices are labeled.

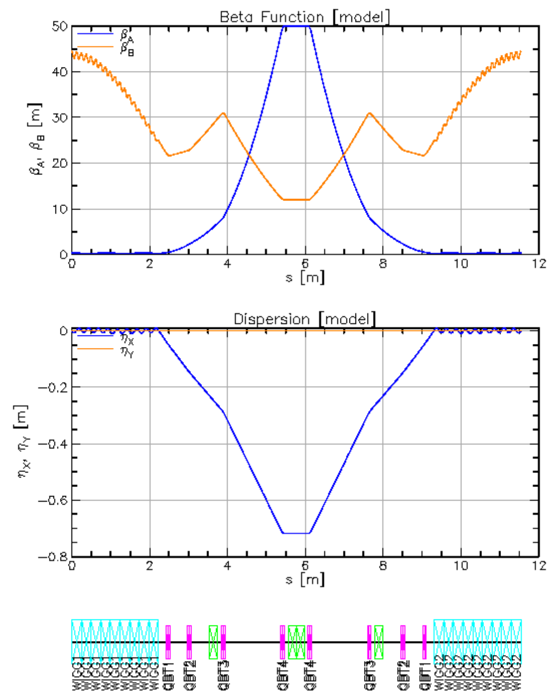

Figure 4: Optics across one wiggler block after optics were matched for the new phase advance. In the layout, wigglers are blue, quadrupoles are purple, and sextupoles are green.

of good horizontal tunes, allowing flexibility in adjusting for the space charge and beam-beam tune shifts.

SEXTUPOLE AND OCTUPOLE CHOICES

Sextupoles were split into two families in the wiggler section. lone pairs of sextupoles were also located in β-function peaks before the cooling section, with strengths chosen for reduction of the W-function [5], defined as

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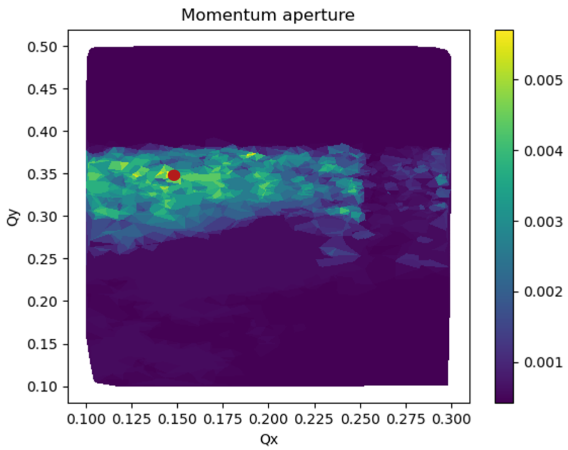

Figure 5: Momentum aperture dependence on tune. Color scale is set to momentum aperture in units of δ.

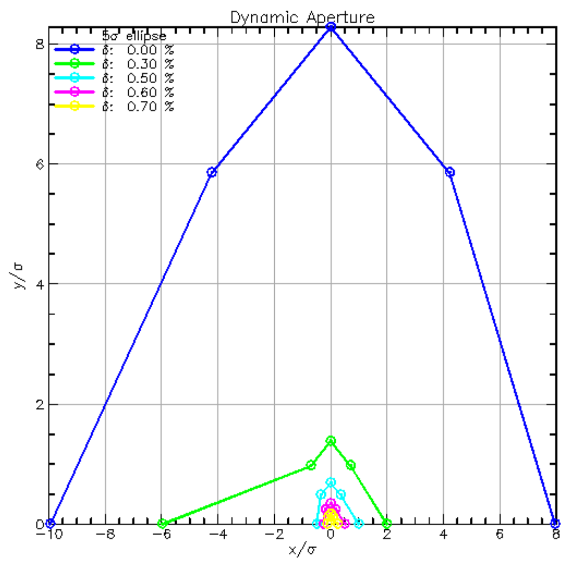

Figure 6: Dynamic aperture after octupole optimization.

$$W = \sqrt{\left(\frac{\partial \alpha}{\partial p_z} - \frac{\alpha}{\beta}\frac{\partial \beta}{\partial p_z}\right)^2 + \left(\frac{1}{\beta}\frac{\partial \beta}{\partial p_z}\right)^2} \tag{2}$$

Due to an odd number of wiggler blocks, W-function correction can not be achieved via a standard two family per plane approach while utilizing all sextupoles. Instead, it was seen that by splitting the correction between the sextupoles in the wiggler sections and the lone pairs at the cooling section the average W-function could be substantially reduced.

Between the wigglers, octupoles were also placed in order to add an extra degree of freedom to the chromatic correction. The octupoles were chosen to reduce the energy dependent tune spread over the desired momentum aperture. This choice of octupole strengths led to a momentum aperture reaching past 5σ in momentum spread shown in Fig. 6.

Relaxing the constraint on the octupoles can increase the transverse size of the momentum aperture while suffering a slight loss in max δ offset (Fig. 7).

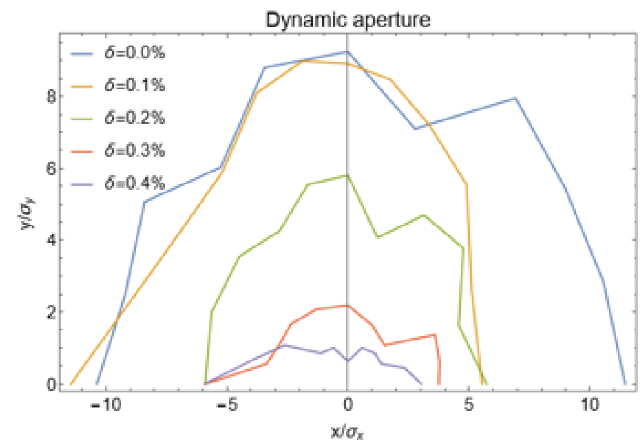

Figure 7: Dynamic aperture after reduction in octupole strengths.

CONCLUSION

The ring electron cooler requires a dynamic aperture of 5σ in order to maintain the beam lifetime needed for the desired cooling rates while allowing the strong wigglers to reduce emittance growth.

The effect of the wigglers on dynamic aperture is reduced by a smart choice of wiggler fields and carefully choosing and matching the phase advances in section where the sextupoles and wigglers are located. Dynamic and momentum apertures were further shown to be improved by tune choice and utilizing octupoles to reduce the energy dependent tune spread, achieving the 5σ for momentum aperture and exceeding the transverse aperture goal.

This scheme provides the transverse aperture with a near 4σ margin as a buffer for magnet errors. The momentum aperture goal was achieved and can be further increased by additional lattice optimization.

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