

# DYNAMIC APERTURE OPTIMIZATION FOR THE RING-BASED ELECTRON COOLER

J. Unger\*, G. Hoffstaetter, Cornell University (CLASSE), Ithaca, NY, USA  
 A. Fedotov, J. Kewisch, S. Seletskiy, Brookhaven National Laboratory, Upton, NY, USA

## Abstract

Electron Ion Collider (EIC) will benefit from cooling protons at the highest collision energy ( $\gamma=294$ ). The required cooling can be provided by the Ring Electron Cooler (REC) - an RF-based non-magnetized electron cooler employing an electron storage ring. As stored electrons cool the EIC protons, their emittance is gradually increased by both the intra-beam and beam-beam scattering. To counteract the heating of electron bunches, eighteen dedicated damping wigglers are utilized. These wigglers require substantially non-linear field with peak value of 2.4 T, occupy a large portion of the electron storage ring, and dominate beam dynamics in the REC. In this paper we describe our approach to maximizing dynamic aperture in the REC, which includes careful optimization of wigglers parameters and development of an elaborate correction scheme for non-linear beam dynamics.

## 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  $5\sigma$  for the transverse and momentum apertures.

## LATTICE OVERVIEW

The REC layout is shown in Fig. 1. It has a trapezoidal shape, with the wiggler section opposing the 170-meter-

Table 1: Baseline Parameters

$N_e$	$1.3 \cdot 10^{11}$
Relativistic $\gamma$	293
Total length [m]	426
Cooling section length [m]	170
Cooling section $\eta_x$ [cm]	100
Cooling section $\beta_{x,y}^*$ [m]	180, 160
Number of wigglers	18
Wiggler length [m]	4.2
Wiggler field [T]	2.4
RF frequency [MHz]	98
RF voltage [kV]	2.1
Emittance (x,y) [nm]	7.8, 7.8
Fractional tune (x,y)	0.16, 0.15
Space charge tune shift (x,y)	0.08, 0.12

long cooling section (CS). The arcs connecting the CD and wigglers contain 10-meter-long straight sections that house the RF and injection systems.

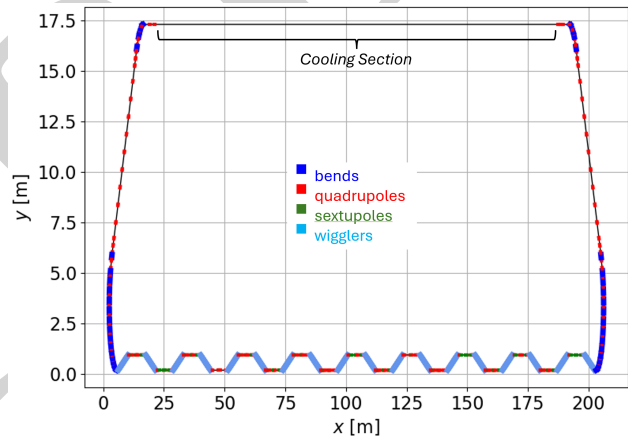


Figure 1: REC floor plan.

In order to reduce emittance growth due to IBS, the  $\mathcal{H}$  inside the wiggler must be minimized:

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

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 ( $\eta'_x$ ) is large in the wigglers, leading to the need to reduce  $\beta_x$ . This is accomplished by adding horizontal focusing in the wigglers, resulting in the optics in Fig. 2. Large  $\beta$ -function is desirable in the cooling section to boost cooling, leading the overall optics in Fig. 3

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

\* jeu8@cornell.edu

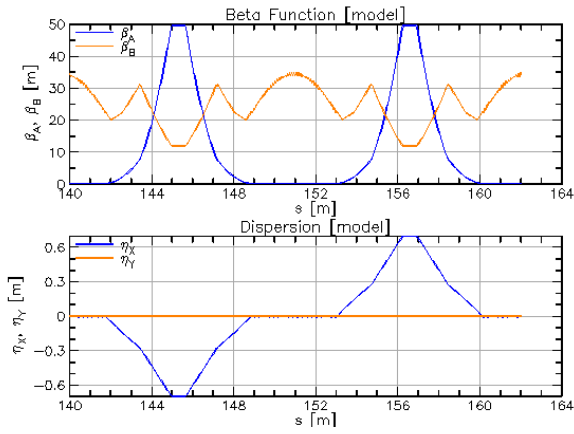


Figure 2: Optics across two wiggler blocks.

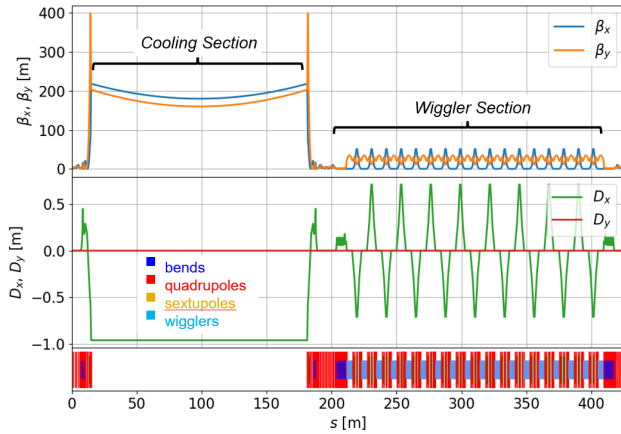


Figure 3: REC optics.

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 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 ADVANCES

The sextupoles are located in short straight sections between wigglers. As wigglers and sextupoles 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. Multiple regions of potential phase advances were tried, with the yellow region in Fig. 4 above  $\phi_y = 0$  being chosen for good DA and easy matching.

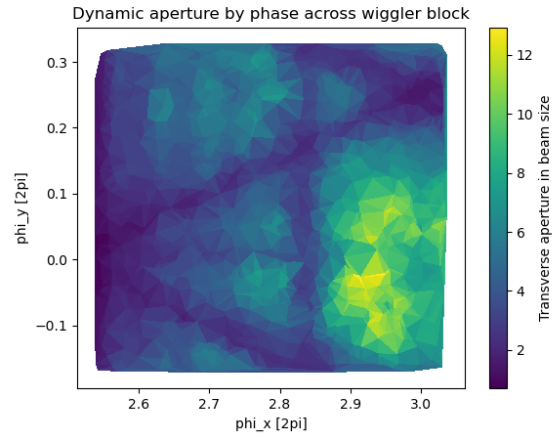


Figure 4: DA scan of wiggler block phase advance.

## SEXTUPOLE OPTIMIZATION

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

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

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 additional 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.

## TUNE CHOICE

As the transverse aperture was well determined by the cancellation of contributions from the sextupoles and wigglers, the tune was chosen to reduce the reduction in DA from space charge effects, determined by particle losses while tracking with a Bassetti-Erskine space charge kick [6] leading to the results in Fig. 5.

This choice of tune coupled with the previous optimizations result in the dynamic aperture of fig 6, resulting in a transverse aperture over the target of  $5\sigma$ , with the momentum aperture just short, leaving room for future improvement.

## CONCLUSION

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

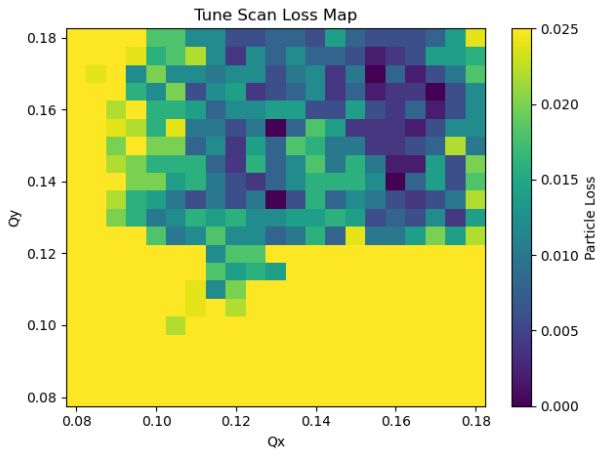


Figure 5: Tune map for tracked beam with space charge color mapped with particle loss as a fraction of the beam over  $10^5$  turns.

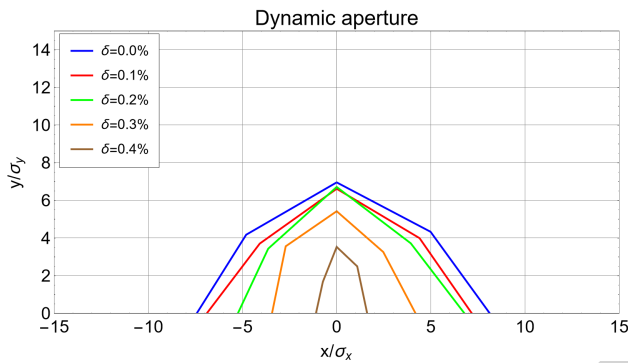


Figure 6: REC DA after tune change to account for space charge footprint.

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, exceeding the transverse aperture goal with the need for minor improvement in the momentum aperture. This scheme further provides the transverse aperture with a margin as a buffer for magnet errors.

## ACKNOWLEDGMENTS

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