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# DYNAMIC APERTURE OF THE RCS DURING BUNCH MERGES

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*Abstract*

The Rapid Cycling Synchrotron (RCS) of the Electron Ion Collider (EIC) will be used to accelerate polarized electrons from 400 MeV to a top energy of 5, 10, or 18 GeV before injecting into the Electron Storage Ring. At 1 GeV, the RCS will perform a merge of two bunches into one, adding longitudinal dynamics that affects the dynamic aperture, depending on the merge parameters. In this paper, results for different merge models will be compared, as well as finding the relationship between the merge parameters of the RCS and its dynamic aperture.

## INTRODUCTION

In order to accelerate electrons to the collision energies of 5, 10, and 18 GeV, the Electron-Ion Collider makes use of the Rapid Cycling Synchrotron (RCS). Electron bunches are injected into the RCS at 400 MeV before being ramped to 1 GeV where they are merged. After the merge they are accelerated to their final energy and extracted to the Electron Storage Ring. During this process, the electrons see a large energy range and merge that they must survive before extraction, leading to the importance of ensuring that dynamic aperture of the ring is sufficient at each step [1].

For this study, the RCS process was split into parts for analysis, with particular emphasis on the merge as a trouble spot. In order to gauge appropriate scaling for the aperture after injection of the round beam, emittance tracking was implemented for the ramp. The required dynamic aperture and emittance calculations were performed using Bmad [2].

## DYNAMIC APERTURE DURING RAMP

The large energy range in the RCS presents a challenge to dynamic aperture, as particles must survive the initial ramp from 400 MeV to 1 GeV, the bunch merge process, and then the ramp from 1 GeV to the target energy. In this study we focus on the scenario of ramping to 18 GeV, requiring two bunches to be merged. In order to track down trouble spots for dynamic aperture during the ramp, runs of 1000 turns were done for several energies in a static ring without ramping and shown in Table 1. As seen the table, the momentum aperture for energies below 5 GeV is smaller than would be desired. This can cause problems as significant time is spent at 1 GeV for the merge. The worst of the range of the RCS is at 400 MeV shown in Fig. 1. The transverse aperture at this energy just below the standard benchmark of $10\sigma$, the vertical is limiting at puts it at $8\sigma$.

At higher energies the momentum aperture increases above $10\sigma_{p_z}$. The transverse aperture begins slightly below the benchmark but improves at higher energies. This improvement is largely due to decreased emittance at higher

Table 1: The Momentum Apertures (MA) for Static Energy Compared to $\sigma_{p_z}$

| Energy [GeV] | MA [$\sigma_{p_z}$] |
|---|---|
| 0.4 | 5.6 |
| 1 | 5.2 |
| 5 | 10.8 |
| 10 | 18.7 |
| 18 | 15.1 |

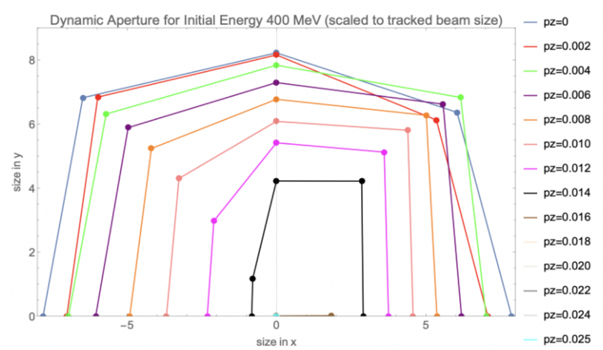


Figure 1: Dynamic aperture without ramping at 400 MeV.

energies from adiabatic damping and radiation. As there is not enough time at any energy for the beam to reach the equilibrium emittance, the reference emittance used for dynamic aperture calculations was obtained by tracking a bunch through the ramp (Fig. 2).

Additional testing of trouble spots was done by taking short segments of the ramp and calculating the dynamic

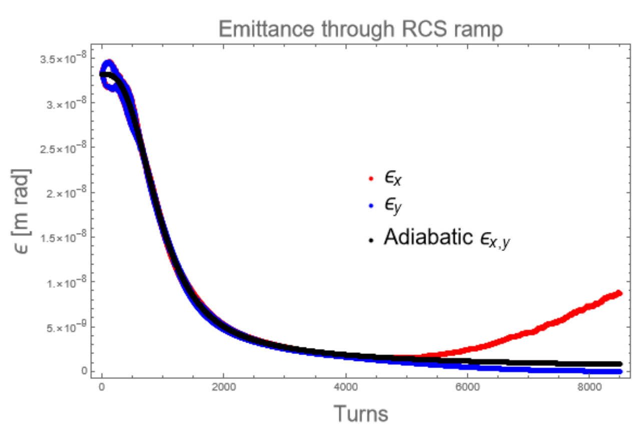


Figure 2: Emittance through 400 MeV to 18 GeV ramp, accounting for radiation. Emittance from adiabatic damping is shown for comparison. Radiation starts making a large difference after 10 GeV.

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Table 2: The Momentum Apertures During 1 GeV Ramps

| **Starting Energy [GeV]** | **MA [$\sigma_{p_z}$]** |
|---|---|
| 0.4 | 2.4 |
| 1 | 2.9 |
| 3 | 7.5 |
| 5 | 10.8 |
| 7 | 14.7 |
| 9 | 18.4 |
| 11 | 22.2 |
| 13 | 21.2 |
| 15 | 18.2 |
| 17 | 15.4 |

aperture over the small portion. In Table 2, the results of this process are shown. Again it is seen that energies below 5GeV suffer a poor energy aperture, and perform worse than in the static energy case. This decrease was able to be reduced by slowing down this portion of the ramp. Slowing down the ramp prior to 5GeV by a factor of 6 was sufficient to recover the momentum aperture of the static 400MeV case.

## DYNAMIC APERTURE DURING MERGE

As seen in the previous section, the momentum aperture for 1 GeV starts smaller than desired, and an increased stay at 1 GeV for the merge will reduce it further along with the added longitudinal dynamics of the merge. In order to test the effect on dynamic aperture, a sample merge was constructed. A two cavity system was chosen to vary smoothly by the functions:

$$V_1(t) = \frac{V_{10}}{1 + E^{-t/(turns \cdot T/10)+8}} \quad (1)$$

$$V_2(t) = \frac{2V_{10}}{1 + E^{t/(turns \cdot T/10)-11}} \quad (2)$$

Where $V_{10}$ is the initial cavity voltage, *turns* length of the merge in turns, and $T$ is the one-turn transit time of the ring. As this is representing a two bunch merge where the second cavity has half of the frequency, the final voltage will be double the initial to maintain the synchrotron frequency. The +8 and -11 shifts are to ensure the second cavity has turned sufficiently on before the first turns off enough to lose particles from the bucket.

By bunch tracking, it was determined that without multi-particle effects, merges longer than 2000 turns would conserve longitudinal emittance. This length was taken as a baseline for a dynamic aperture calculation, as including more effects would increase the time needed at this energy. The resulting calculation, shown in Fig. 3, gives a similar momentum aperture compared to the previous result at 1 GeV. The transverse aperture now performs worse, only reaching just above 4$\sigma$ in the horizontal.

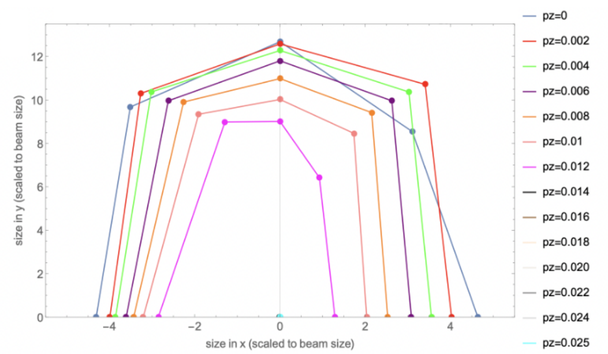


Figure 3: Dynamic aperture during a 2000 turn merge.

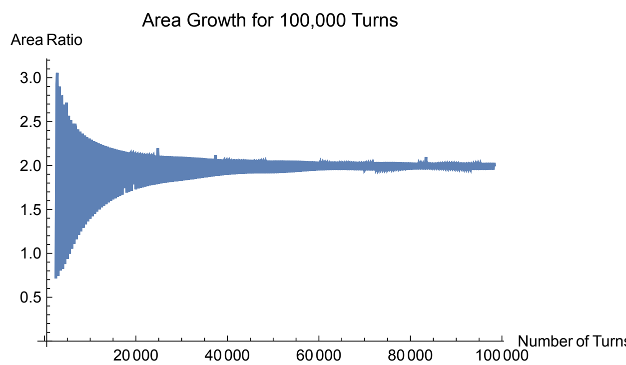


Figure 4: Ratio of final to initial single particle emittance for different merge lengths. Minimum increase for a full bunch should be a ratio of 2.

## SINGLE PARTICLE DYNAMICS DURING MERGING

In order to better understand the dynamics of the merge, single particle studies of merge behavior have begun. This aims at decreasing total merge time by improving merge performance, which indirectly is a strategy of increasing dynamic aperture. A simple model was created where a particle is tracked through a one-turn matrix and two cavities. This particle starts with a small initial longitudinal offset that can be used to calculate single particle emittance before the the merge. This is done by integrating over the particle's phase space after several turns. After the merge this process is repeated to obtain a ratio of emittances. In this case of the longitudinally symmetric bunch merge, the expected minimum increase for a full bunch is a factor of 2. In the single particle case, the emittance ratio oscillates based on the number of turns in the merge. Initially this oscillation is quite large, eventually damping down to the expected value of 2 (Fig. 4). This oscillation happens to have a period of about twice the synchrotron period.

In the case of a full bunch, it is expected the end emittance would increase by a factor of 2 at slow speeds, and then a linear increase as the speed is increased. In the single particle case this is not observed, however a fit to the peaks of the oscillations gives a similar behavior seen in Fig. 5.

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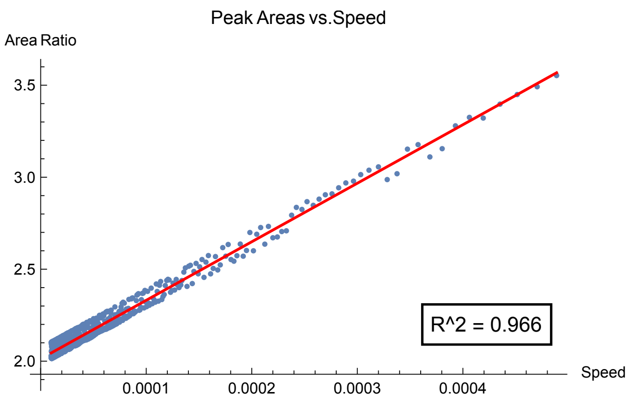


Figure 5: Single particle emittance ratio fit to the peaks of Fig. 4. Peaks vary linearly with merge speed.

## CONCLUSION

The RCS needs sufficient dynamic aperture along the entire process of initial ramp, merge, and final ramp. It is seen that at energies below 5GeV the momentum aperture is about half the benchmark. This problem becomes worse with ramping, although slowing the ramp regains the aperture, but cannot increase it beyond the static energy case. The merge takes place at 1GeV, in the trouble region, where the added time of merge decreases the transverse aperture. Studying single particle merge dynamics can lead to improve merge performance and increasing dynamic aperture. Additional changes, such as introducing a booster that bypasses some of the region below 5GeV, can also be beneficial in improving beginning to end dynamic aperture in the RCS.

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