ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB010

FULL RANGE TUNE SCAN STUDIES USING GRAPHICS PROCESSING UNITS WITH CUDA IN EIC BEAM-BEAM SIMULATIONS*

D. Xu†, Y. Luo, C. Montag, Brookhaven National Laboratory, Upton, NY, USA
Y. Hao, Michigan State University, East Lansing, MI, USA
J. Qiang, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The hadron beam in the Electron-Ion Collider (EIC) suffers high order betatron and synchro-betatron resonances. In this paper, we present a weak-strong full range (0.0 ~ 0.5) fractional tune scan with a step size as small as 0.001. Multiple Graphics Processing Units (GPUs) are used to speed up the simulation. A code parallelized with MPI and CUDA is implemented. The good tune region from weak-strong scan is further checked by the self-consistent strong-strong simulation. This study provides beam dynamics guidance in choosing proper working points for the future EIC.

INTRODUCTION

The working point, i.e., the fractional part of the betatron tunes, is one of the key parameters in circular synchrotrons. The performance of a collider depends sensitively on the working point. Due to the detuning mechanism, the beam-beam force introduces a spread in the beam tunes. The working point specified by the unperturbed tunes becomes a working area [1]. The unperturbed working point is usually close to the main diagonal line $\nu_x = \nu_y$ so that the footprint fits into a “resonance free” region in the tune space.

In EIC, the ion beam size should match the electron beam size at IP. Therefore a flat ion beam is necessary [2]. It would be dangerous when the unperturbed working point is too close to the main diagonal line — a minor change in the horizontal emittance gives rise to a large change in the vertical emittance. According to our previous study, the hadron beam in EIC suffers not only the betatron resonances but also the synchro-betatron resonances [3]. As a result, the coupling stopband has to avoid when choosing the working point for EIC. In EIC Conceptual Design Report (CDR), the difference of $|\nu_x - \nu_y|$ has to be increased to 0.018 to eliminate the discrepancy between the crab crossing and head-on collision [4]. As the distance from the unperturbed working point to the main diagonal line increases, the higher-order betatron resonances, and synchro-betatron resonances are unavoidable. Other regions away from the main diagonal line in the tune space may also be optional. A full-range tune scan may be beneficial to the EIC design.

In this study we would like to answer a few questions from the viewpoint of beam-beam dynamics

- Is it possible to choose the working point away from the main diagonal line?
- Which is the preferred working point?

A full range scan is done first by weak-strong simulation. Then the strong-strong simulation is used to refine the scan result in a small area.

COMPUTATION RESOURCES AND CODE

The proton beam performance is sensitive to the working point. In this study, the horizontal and vertical tunes vary in steps of 0.001. The scan range is from 0.001 to 0.5 in both planes. There are 250, 000 jobs in total. One million macroparticles are tracked by 10, 000 turns for each job. The beam parameter table used in the simulation is in [2] or [4].

In the weak-strong simulation, the motion of every particle is independent of each other. With the help of high-performance parallel computing provided by the Graphics Processing Unit (GPU), the same process runs on multiple threads simultaneously. Our study employs 4 Nvidia Tesla K80 GPUs for each job.

Nvidia has focused on applying GPUs to scientific programming, using double precision. The Compute Unified Device Architecture (CUDA) is a parallel computing architecture developed by Nvidia. CUDA offers the data-parallel C++ Thrust API to use when programming [5]. A hybrid C++ code parallelized with Message Passing Interface (MPI) and CUDA is implemented. The computing performance is compared in Table 1. The total time is about 86.8 days×nodes. With more than 10 nodes running at the same time, the full range tune scan can be finished in one week.

Table 1: Performance Comparison of MPI Only and Hybrid (MPI and CUDA) Code

	MPI only	Hybrid (MPI + CUDA)
macro particles	1 million	
nodes	1	
tracking turns	10,000	
tasks	32	4
elapsed time	5 minutes	30 seconds

The Faddeeva error function is frequently used when computing the beam-beam kick in the weak-strong simulation. Reference [6] reviews the Faddeeva implementations on the GPU or CPU. Our code uses the Faddeeva package by MIT [7] on CPU. A GPU variant is developed based on this version.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy
† dxu@bnl.gov

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB010

TUNE SCAN RESULTS

For every specific working point, the last 60% of tracking data is collected. The RMS beam sizes are calculated from the phase space coordinates,

$$\sigma_x = \sqrt{< x^2 > - < x >^2}$$
$$\sigma_y = \sqrt{< y^2 > - < y >^2} \tag{1}$$

Then the beam size growth rates are linearly fitted from the turn-by-turn tracking data

$$g_x = \frac{1}{\sigma_{x0}} \frac{d\sigma_x}{dn}, \quad g_y = \frac{1}{\sigma_{y0}} \frac{d\sigma_y}{dn} \tag{2}$$

Figure 1 presents the weak-strong tune scan results. More resonance lines appear in the vertical plane. Many coupling resonances have to be avoided. The stopband close to the main diagonal line is also clear.

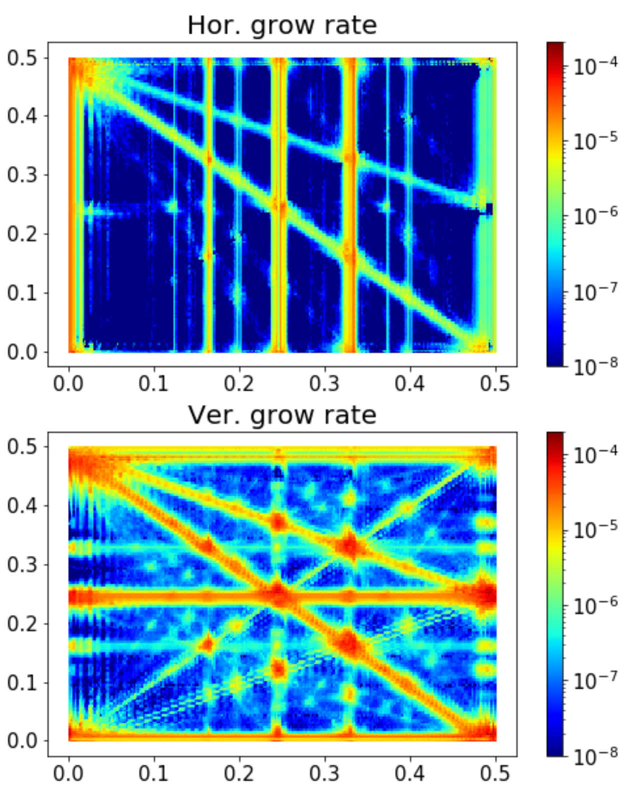

Figure 1: Beam size growth rates by weak-strong tune scan, top: horizontal growth rate, bottom: vertical growth rate.

As pointed out in [4], 10,000 turns are not sufficient to get the accurate growth rates in the weak-strong simulation. The beam-beam coherent instability should be avoided too. It is essential to further refine the tune scan results by the self-consistent strong-strong simulation. Only “good region” is checked by the strong-strong simulation. The good region is defined where both horizontal and vertical growth rates are small, as shown in Fig. 2.

The islands labeled as A and B with a large area in Fig. 2 are far away from the main diagonal line. The strong-strong simulations are performed in islands A and B.

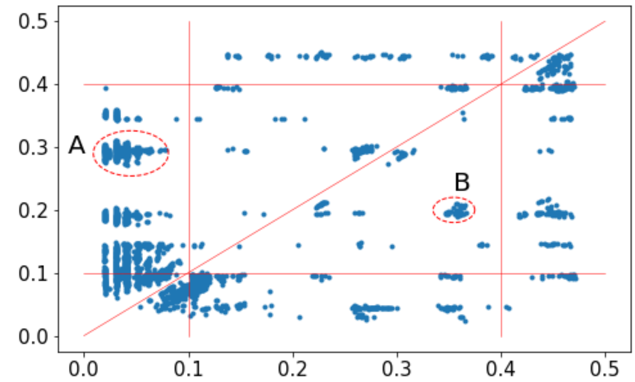

Figure 2: Good region determined by the dark blue area in Fig. 1. The islands A and B are selected to do the strong-strong optimization.

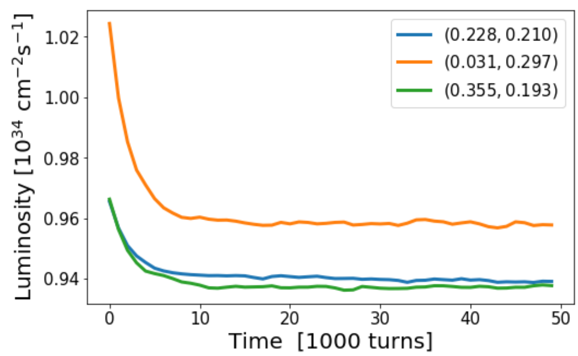

Figure 3: The luminosity evolution by strong-strong simulation. $(0.228, 0.210)$ is the working point for EIC CDR.

Two new working points are found in A $(0.031, 0.297)$ and B $(0.355, 0.193)$. The luminosity is compared in Fig. 3 and the beam size evolution is shown in Fig. 4. Without significant loss of the luminosity, both horizontal and vertical growth are reduced at the two new working points. It proves that we can choose the working point away from the main diagonal line.

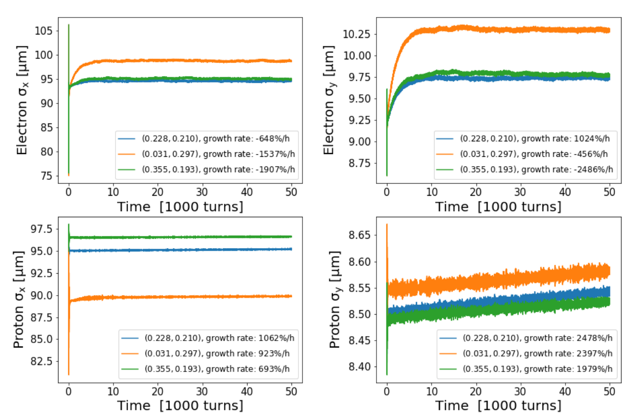

Figure 4: The beamsize evolution by strong-strong simulation. $(0.228, 0.210)$ is the working point for EIC CDR.

FURTHER STUDY ABOUT (0.355,0.193)

We use frequency map analysis (FMA) to study the beam-beam dynamics at the new working point. The footprint of $(0.355, 0.193)$ is present in Fig. 5. The synchro-betatron resonance in Fig. 5 is

$$\nu_x - 2\nu_y + 4\nu_z = 0 \tag{3}$$

The harmonic crab cavity can be used to mitigate the synchro-betatron resonance [8]. The simulation results are present in Fig. 6. It shows that the second-order harmonic crab cavity works better at the new working point.

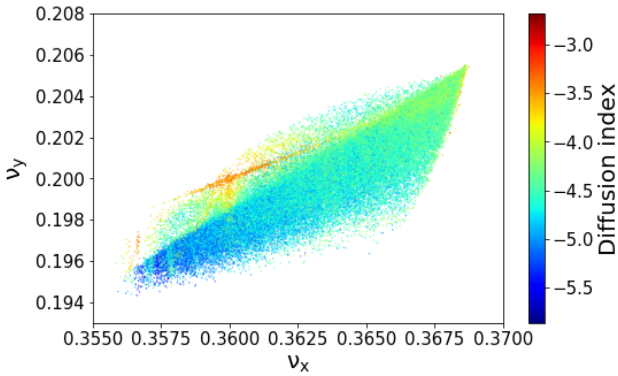

Figure 5: The frequency map for the new working point $(0.355, 0.193)$.

From Fig. 5, the footprint crosses the 5th order resonance line $\nu_y = 0.2$. In the beam-beam simulation, it is not a problem because the resonances with odd coefficients of ν_y are not excited in the horizontal crab crossing scheme. However, it may not be the truth in the dynamic aperture (DA) study. The new working point$(0.355, 0.193)$ may be sensitive to the magnetic errors. The real machine needs comprehensive consideration.

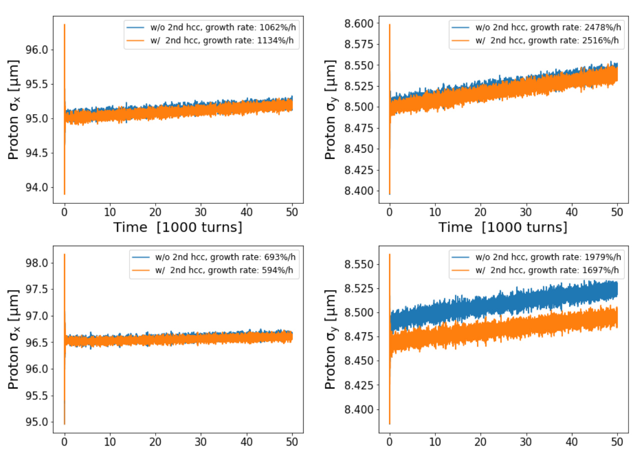

Figure 6: The ptroton beam size evolution by strong-strong simulation when harmonic crab cavity is used, the top two figures are for the EIC CDR working point $(0.228, 0.210)$, and the bottom two figures are for the new working point $(0.355, 0.193)$.

SUMMARY

In this article, we present the full range tune scan for the EIC CDR parameter set. After the subsequent optimization by the strong-strong simulation, two new working points are found. From the viewpoint of beam-beam dynamics, the new working points mitigate the proton emittance growth rates without loss of the luminosity. We show the possibility of moving the working point far away from the main diagonal line in this paper. We also prove the capability to do the full range tune scan. A further scan is still ongoing.

ACKNOWLEDGEMENT

Authors acknowledge HPCC resources provided by the iCER at Michigan State University.

REFERENCES

[1] A. W. Chao, "Nonlinear beam-beam resonances", US/CERN School on Particle Accelerators, Sardinia, Italy, Rep. SLAC-PUB-3545, Jan. 1985.

[2] Y. Luo *et al.*, "Beam-Beam Related Design Parameter Optimization for the Electron-Ion Collider", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB028.

[3] D. Xu, Y. Hao, Y. Luo, and J. Qiang, "Synchrobetatron resonance of crab crossing scheme with large crossing angle and finite bunch length", *Phys. Rev. Accel. Beams*, vol. 24, no. 4, p. 041002, Apr. 2021. doi:10.1103/physrevaccelbeams.24.041002

[4] D. Xu, Y. Hao, Y. Luo, C. Montag, and J. Qiang, "Numerical Noise Study in EIC Beam-Beam Simulations", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB008.

[5] Thrust, https://developer.nvidia.com/thrust

[6] A. Oeftiger *et al.*, "Review of CPU and GPU Faddeeva Im-plementations", in *Proc. 7th Int. Particle Accelerator Conf.(IPAC'16)*, Busan, Korea, May 2016, pp. 3090–3093. doi:10.18429/JACoW-IPAC2016-WEPOY044

[7] Faddeeva Package, http://ab-initio.mit.edu/wiki/index.php/Faddeeva_Package.

[8] D. Xu, Y. Hao, Y. Luo, C. Montag, and J. Qiang, "Study of Harmonic Crab Cavity in EIC Beam-Beam Simulations", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB009.