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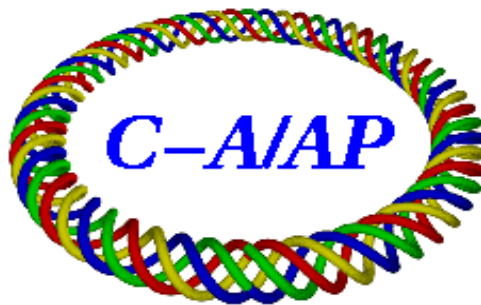
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Wide range tune scan simulations for RHIC

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In this article, we report on numerical simulations to calculate dynamic apertures over wide tune ranges for RHIC. Three Blue ring lattices are used as the starting points: 2012 255 GeV polarized proton lattice, 2010 100 GeV ion run lattice, and 2012 100 GeV ion run lattice. For each lattice, we scan the fractional tunes from (0.011, 0.001) to (0.991, 0.990) with a step size of 0.001 by adjusting the main arc quadrupoles QFs and QDs. The tracking results are presented, together with the resonance structures, β -beats w.r.t the base lattices, and nonlinear chromaticities.

1 Lattice and beam parameters

In this study, we used three Blue ring lattices as the base lattices: 2012 255 GeV polarized proton lattice, 2010 100 GeV ion run lattice, and 2012 100 GeV ion run lattice. The base lattices have the nominal tune settings as in operation (see Tab. 1). The main difference between the 2010 and 2012 ion run lattices are the integer tunes. The integer tunes of 2010 RHIC ion run lattice are (31, 32). While for the 2012 RHIC ion run lattice, they are (28, 29). The increased integer tunes for the 2010 RHIC ion run lattices was used to reduce the transverse emittance growth rate due to intrabeam scattering (IBS) [1]. For simplicity, we call the 2010 RHIC ion run lattice as the IBS-suppression lattice and the 2012 RHIC ion run lattice as the standard lattice.

In the following we investigate the dynamic aperture's dependence on the fractional tune with Sim-Track [2]. We scan the fractional tunes below the diagonal in the tune space from (0.011, 0.001) to (0.991, 0.990) with a step size of 0.0001. The tunes are simply adjusted with the main arc quadrupoles QFs and QDs from the base lattices. By doing so, the β -beat w.r.t. the well tuned base lattices can become large and linear motion could become unstable near the integer and half-integer resonances.

Table 1 lists the lattice and beam parameters for the three base lattices. For the two ion lattices, we will use Au ions although in the 2012 RHIC run we did not collide Au with Au. For the proton run, we will focus on the impact of beam-beam effects on the dynamic aperture. In the simulations, the beam-beam interactions occur at IP6 and IP8. The bunch intensity is set to 1.60×10^{11} which gives the beam-beam parameter of 0.016 for both IPs. The particle's initial relative momentum error is 0.0005, which is 3.6 times the rms relative momentum spread. For the ion run lattices, we focus on the off-momentum dynamic aperture. In the simulation we exclude the beam-beam interactions. The particle's initial relative momentum error is 0.0015. The RF bucket height (dp/p0) in this case is 0.0019.

Fig. 1 shows the tune space with betatron resonance lines up to the 10th order. Along the diagonal, the largest tune spaces free of low-order resonances are found below 0.1, above 0.9, close to 0.5, and close to 1/3 and 2/3. However, close to these regions strong low order resonances are present (i.e. integer, half-integer and third-order resonances). To be able to operate accelerators at these working points, one should carefully control linear optics, machine imperfections, and third order resonance driving terms.

2 Results

2.1 255 GeV p-p run lattice

Fig. 2 shows the dynamic aperture as a function of the tune using the 255 GeV p-p run Blue ring lattice. The horizontal axis is the fractional vertical tune without beam-beam. The vertical axis is the dynamic aperture with beam-beam in units of the rms transverse beam size σ . In this study, the normalized rms transverse emittance is $2.5 \mu\text{m}$.

Table 1: Optics and beam parameters of the three base lattices

quantity	proton run lattice	ion run lattices	
	2011 p-p lattice	IBS-suppression lattice	standard lattice
Energy	255 GeV	100 GeV	100 GeV
Lorentz factor	271	107	107
nominal working point	(28.695, 29.685)	(31.23, 32.22)	(28.23, 29.22)
β^* at IP6 and IP8	0.65 m	0.7 m	0.7 m
β^* at other IPs	7.5 m	5 m	5 m
first order chromaticities	(1,1)	(1,1)	(1,1)
second order chromaticities	(2500, 4650)	(-4100,-1700)	(2600, 177)
third order chromaticities	(0.71e6, 0.55e6)	(-0.7e6, -0.2e6)	(-0.5e6, -0.2e6)
rms normalized transverse emittance	2.5 μm	2.5 μm	2.5 μm
rms bunch length	2.5 ns	0.8 ns	0.8 ns
RF bucket height	1.1×10^{-3}	1.9×10^{-3}	1.9×10^{-3}
particle's initial (dp/p_0) in simulation	0.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}
beam-beam included in tracking	Yes	No	No
bunch intensity	1.6×10^{11}	-	-
beam-beam parameter (total, 2 IPs)	-0.016	-	-

The linear motion is unstable when the fractional tunes approach 0.0, 1.0, and 0.5, which is due to the large β -beat introduced by the tune matching using the arc main quadrupoles only. To investigate the dynamic apertures in those regions, dedicated lattices would be required instead of this simplified approach.

Including beam-beam interactions, the tunes of the zero amplitude particles are shifted down by the beam-beam parameter [3]. If the tunes without beam-beam are above a resonance line and the distance with respect to this resonance is less than the beam-beam parameter, the beam-beam tune shift will push some particles across this resonance line leading to a possible reduction of the dynamic aperture. On the other hand, if the tune without beam-beam is below a resonance line, particles will be pushed away from this resonance by the beam-beam tune shift and the dynamic aperture may not be affected by this resonance.

From Fig. 2, the current nominal working point (28.695, 29.685) is in a good tune area where the dynamic apertures are above 7σ . Other regions with large dynamic apertures can be seen around 0.63, 0.73, 0.77, 0.82, and so on. For the near integer tunes (less than 0.1 away from the integers), Fig. 2 shows that the dynamic aperture is larger for tunes above integer with respect to the ones below. The same feature is observed near half-integer. However, several studies have shown that operating above integer or half integer resonances could lead to instabilities due to coherent beam-beam effects [5]. These effects are not taken in the weak-strong model used for dynamic aperture calculations. The dynamic apertures around the RHIC original design tunes (0.19,0.18) are below 6σ [4]. For the p-p run lattice, polarization preservation [6] also has to be taken into account when choosing the appropriate working point.

2.2 100 GeV ion run lattices

Fig. 3 and 4 show the dynamic aperture's dependence on the fractional vertical tune with the IBS-suppression and standard ion lattices. The structures or envelopes of the dynamic aperture w.r.t. the fractional tune are similar for both lattices and driven by the resonance structure shown in Fig. 1.

However, comparing Fig. 3 and 4, the standard lattice gives larger off-momentum dynamic aperture than the IBS-suppression lattice in most of the tune regions. For example, for the nominal fractional tunes (0.23, 0.22), the off-momentum aperture for the IBS-suppression lattice is 3.5σ , while for the standard lattice, it is 4.5σ . In the 2012 RHIC ion runs, we adopted the standard lattices resulting in a improved lifetime due to the larger off-momentum dynamic aperture [7].

From Fig. 4, for the standard lattice, the tunes above $1/2$ give larger off-momentum aperture than the tunes below $1/2$. The good tune areas with off-momentum dynamic aperture larger than 5σ are located around 0.63, 0.68, 0.72, 0.77, and so on. For the ion run lattices, besides the off-momentum aperture, we also need to provide $(2k+1)\pi/2$ phase advances between the pickups and kickers of transverse stochastic cooling [8].

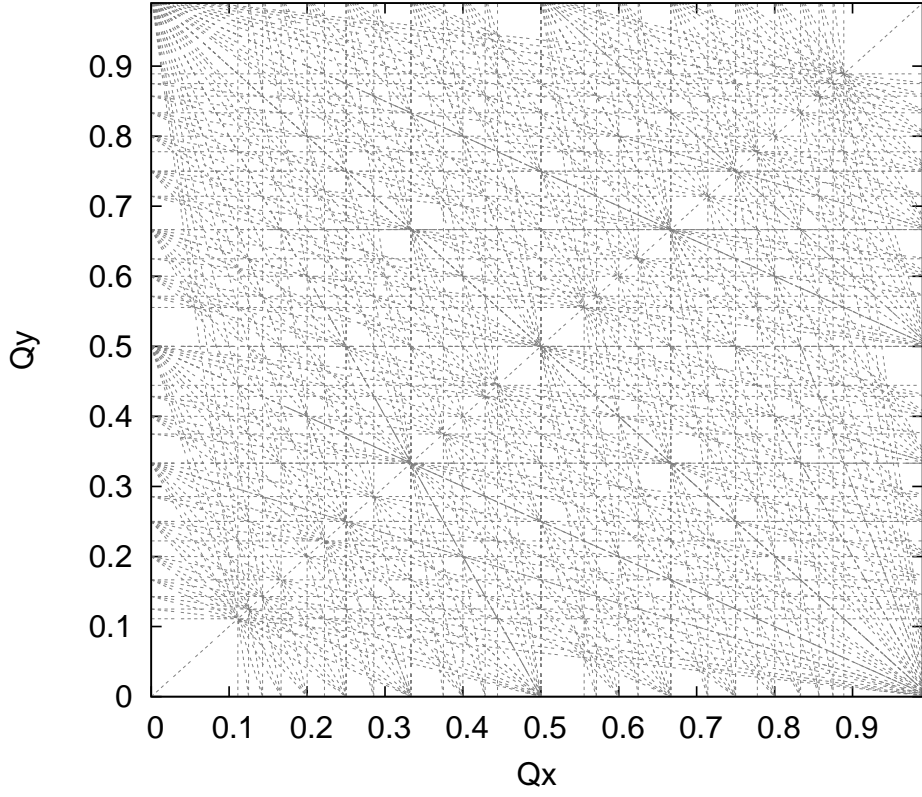


Figure 1: Resonance lines up to 10th order. Along the diagonal, there are wide low resonance free tune spaces below 0.1, above 0.9, on both sides of $1/2$, $1/3$, $2/3$.

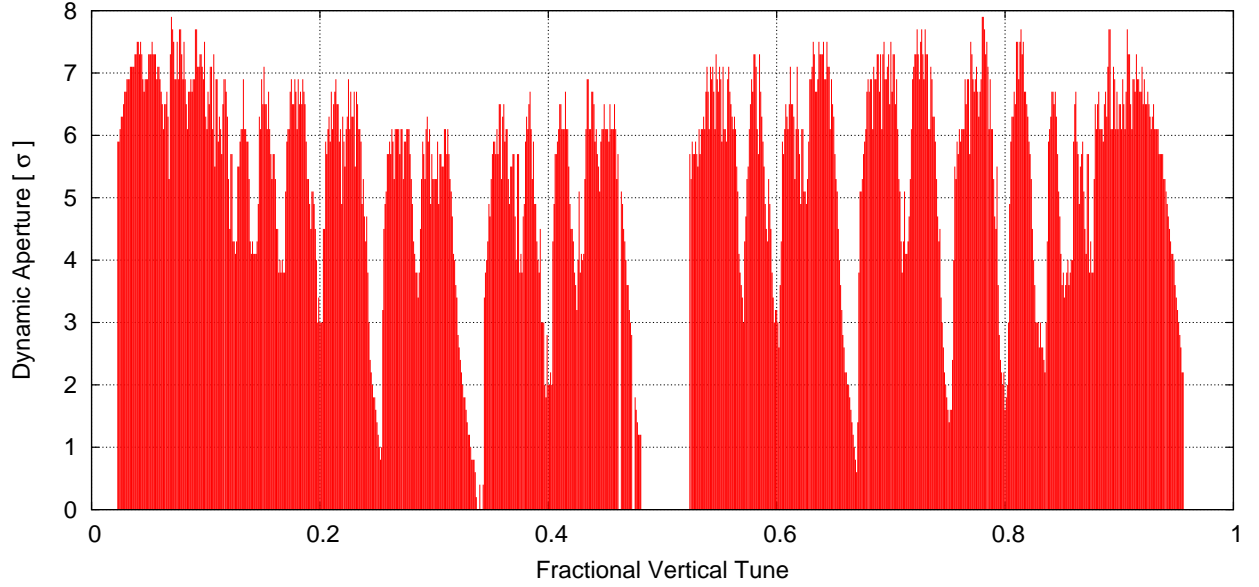


Figure 2: The dynamic aperture versus the fractional vertical tune with the 255 GeV p-p lattice. The fractional horizontal tune is always 0.01 higher than the fractional vertical tune. Beam-beam interactions at IP6 and IP8 are included.

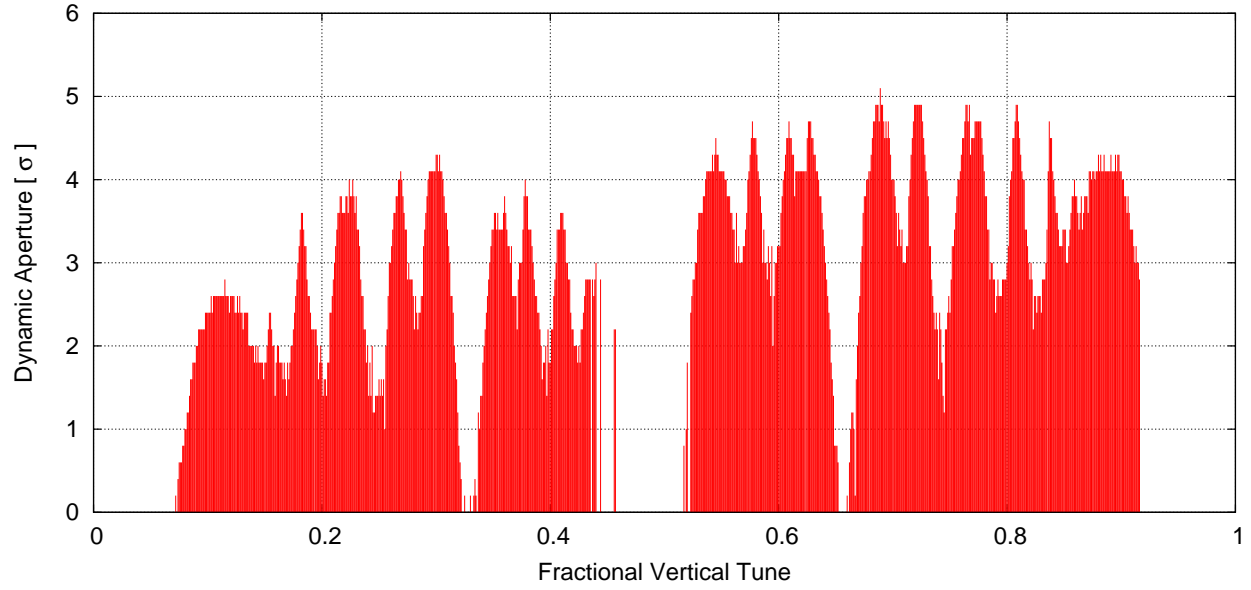


Figure 3: The dynamic aperture versus the fractional vertical tune with the IBS-suppression ion run lattice. The integer tunes are (31, 32). Beam-beam interactions are not included.

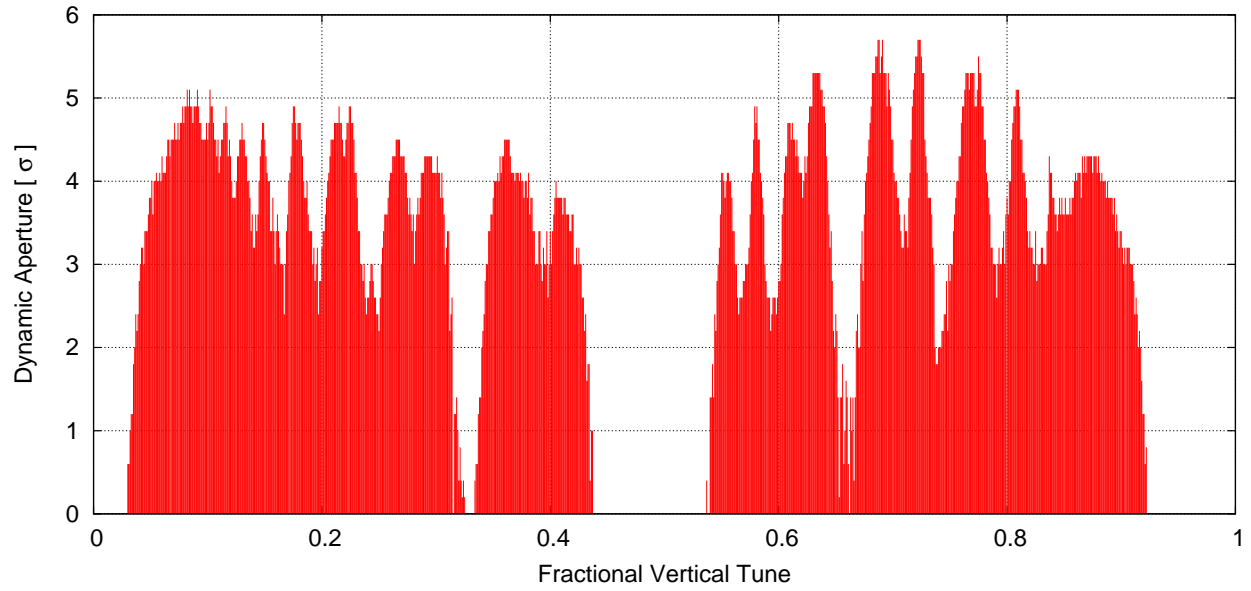


Figure 4: The dynamic aperture versus the fractional vertical tune with the standard ion run lattice. The integer tunes are (28, 29). Beam-beam interactions are not included.

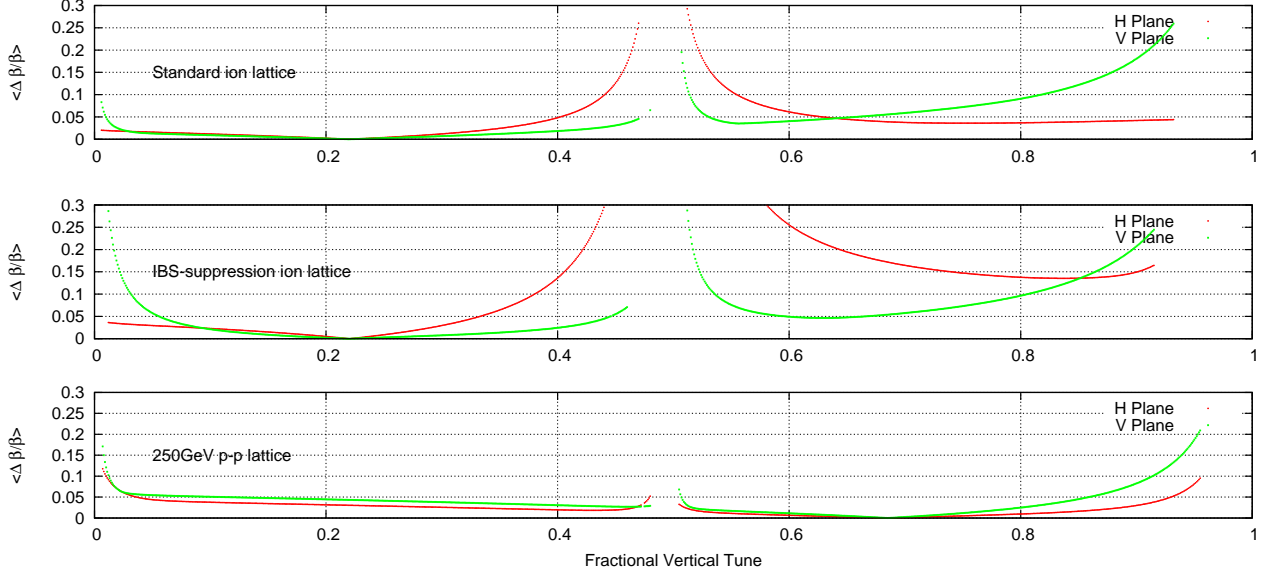


Figure 5: $\langle \Delta|\beta|/\beta \rangle$ versus the vertical fractional tune.

3 Discussion

3.1 β -beat

In the above scans, the tunes were re-matched using the arc main quadrupoles QFs and QDs only. This could introduce optics function distortions along the ring. Here we calculate the averaged β -beat w.r.t. to the base lattices along the ring. Considering that the base lattices are well tuned, the averaged β -beats w.r.t. the base lattices should reflect the optics distortions of the new lattices.

Fig. 5 shows the averaged β -beat versus the vertical fractional tune in the above tune scans. For the 255 GeV p-p run lattices, the averaged relative β -beat is below 10% for tunes between 0.1 to 0.9. For the IBS-suppression ion run lattices, the averaged relative β -beat is larger than 15% with tunes above 0.4 in one or both planes. For the standard ion run lattices, the averaged relative β -beat is below 10% with tunes below 0.4, and between 0.6 and 0.8. The IBS-suppression lattice gives a larger averaged β -beat in most tune areas than the standard lattice.

3.2 Nonlinear Chromaticities

Nonlinear chromatic effects reduce the off-momentum dynamic aperture. Fig. 6 and 7 show the second and third order chromaticities versus the fractional vertical tune. For all of the three lattices, when the tunes are close to half-integer or integer, the second and third order chromaticities diverge.

For the 255 GeV p-p run lattices, the vertical second order chromaticities with tunes below 0.5 are smaller than the one for tunes above 0.5. When the fractional tune is below 0.2, the horizontal second order chromaticity is below 2500. When the tune is above 0.8, the horizontal second order chromaticity is above 5000. Simulation shows that the near-integer tunes above integer give bigger dynamic apertures than the near-integer tunes below integer.

Around the nominal fractional tunes (0.23, 0.22), the IBS-suppression ion run lattices give larger second and third order chromaticities than the standard ion run lattices, which is the reason that we adopted the standard lattice for the 2012 ion runs.

For the standard ion lattices, the second order chromaticity for the nominal tunes (0.23, 0.22) are (2600, 177). The second order chromaticity for the working point (0.69, 0.68) are (1400, 3200). Simulation shows that the working point (0.69, 0.68) gives a larger off-momentum dynamic aperture than the nominal working point. The reason may be that with a positive horizontal chromaticity, the horizontal off-momentum tune of the nominal tunes (0.23, 0.22) will reach to 0.25 which is a 4th order betatron resonance. While for the working point (0.69, 0.68), the horizontal off-momentum tune will reach to 0.7 which is a 10th order betatron resonance.

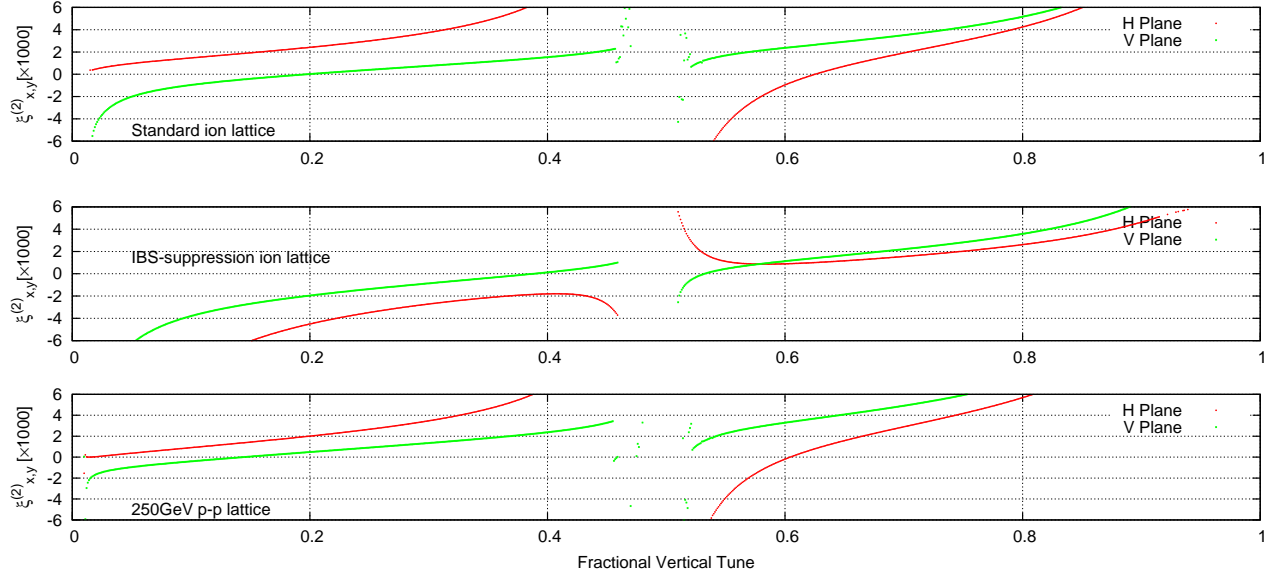


Figure 6: Second order chromaticities versus the fractional vertical tune.

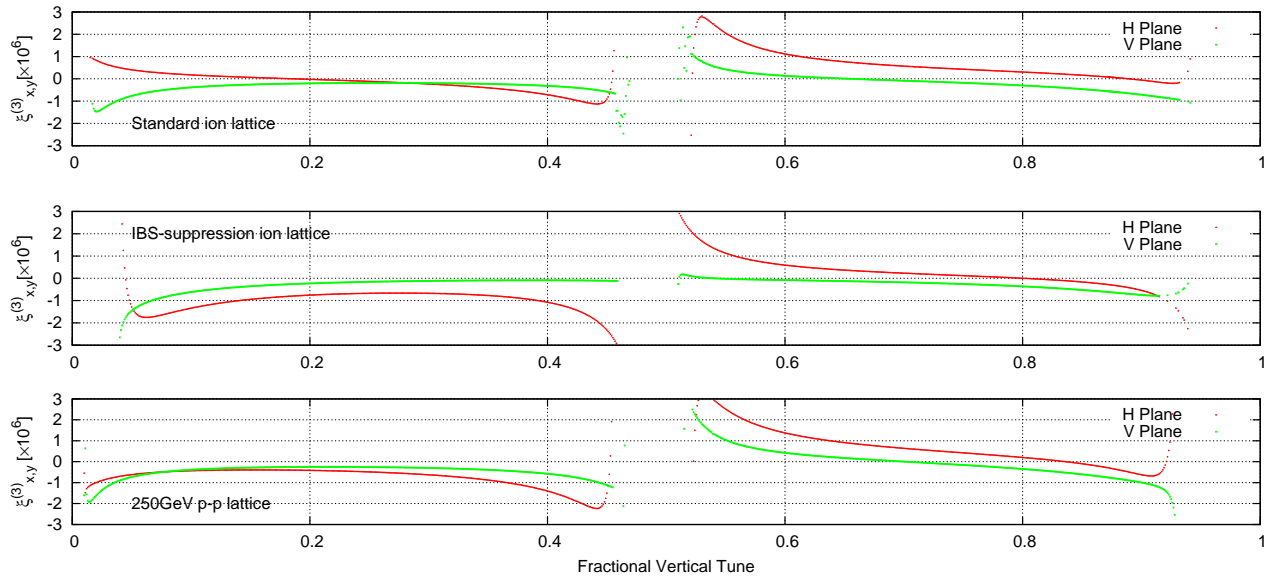


Figure 7: Third order chromaticities versus the fractional vertical tune.

3.3 General Rules in Working Point Search

The dynamic aperture in RHIC is mainly determined by the beam-beam interactions, the nonlinear field errors in the interaction regions, and the nonlinear chromaticities with low β^* s. Numerical simulation of tune scan is a fast and easy way for the searching of good working points.

For the proton run lattice, we would like to choose a working point to provide a good beam lifetime with beam-beam interactions and to maintain the proton polarization on the ramp and at store. There should be an enough tune space to accommodate the beam-beam tune spread. Proper betatron phase advances between beam-beam and beam-beam compensations are also required to minimize the beam-beam resonance driving terms. Also we should note that several studies have shown that operating above integer or half integer resonances could lead to instabilities due to coherent beam-beam effects. These effects are not taken in the weak-strong model used for dynamic aperture calculations.

For the ion run lattice, to obtain a large off-momentum dynamic aperture, we would like to minimize the chromatic effects. For RHIC, in principle, we could reduce the nonlinear chromaticities by adjusting the phase advances between IP6 and IP8 [9]. However, currently we are not able to independently adjust them since all the main arc focusing and defocusing quadrupoles are on the same power supply circuits. Choosing different tunes may affect the nonlinear chromaticities, as shown in Fig. 6 and 7. In addition, we need to keep the $(2k + 1)\pi/2$ phase advances between the pickups and kickers of transverse stochastic cooling.

4 Summary

We carried out numerical simulation to calculate the dynamic aperture over the full fractional tune range for three Blue ring lattices. We scanned the fractional tunes from (0.011,0.001) to (0.991, 0.990) with a step size of 0.0001 by adjusting the main arc quadrupoles QFs and QDs. The tracking results are presented, together with the β -beats w.r.t the base lattices, and nonlinear chromaticities. The general rules for searching good working points are discussed.

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