Tracking Simulations Near Half-Integer Resonance at PEP-II

Y. Cai and Y. Nosochkov
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

Beam-beam simulations predict that PEP-II luminosity can be increased by operating the horizontal betatron tune near and above a half-integer resonance. However, effects of the resonance and its synchrotron sidebands significantly enhance betatron and chromatic perturbations which tend to reduce dynamic aperture. In the study, chromatic variation of horizontal tune near the resonance was minimized by optimizing local sextupoles in the Interaction Region. Dynamic aperture was calculated using tracking simulations in LEGO code. Dependence of dynamic aperture on the residual orbit, dispersion and $\beta$ distortion after correction was investigated.

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INTRODUCTION

PEP-II [1] has been operating at the betatron tune \( \nu_x/\nu_y \) close to 24.569/23.639 in the High Energy Ring (HER) and 38.649/36.564 in the Low Energy Ring (LER). These working points were selected experimentally for a reliable machine performance, good luminosity and beam lifetime. However, the beam-beam simulations predict that luminosity can be increased by operating betatron tune very close and above the half-integer resonance. Fig. 1 shows the LER tune diagram with synchro-betatron resonances up to the 4th order and a contour plot of the single bunch luminosity. Calculation of luminosity was done using the beam-beam code developed at SLAC [2] which has been recently upgraded to the three dimensional version.

The difficulty of operating close to half-integer resonance comes from enhancement of the resonance effects on betatron motion. It is well known that perturbation of β function created by focusing errors depends on tune ν as

\[
\frac{\Delta \beta}{\beta}(s) = \frac{1}{2 \sin 2\pi \nu} \int_0^\infty \beta(l) \Delta K_1(l) \cos 2\phi(s,l) dl, \tag{1}
\]

where \( \mu \) is phase advance, \( \phi(s,l) = \pi \nu - |\mu(s) - \mu(l)| \), and \( \Delta K_1 \) is a focusing error created mainly by quadrupole field imperfections, horizontal orbit at sextupoles, and momentum error. Close to half-integer resonance, growth of \( \Delta \beta/\beta \) comes from the resonance term \( \sin 2\pi \nu \) which behaves as \( 1/\Delta \nu \) when distance to the resonance is as small as \( \Delta \nu \ll 1/2\pi \). On the other hand, orbit and dispersion are not excited by the half-integer resonance.

For significant enhancement of luminosity, fractional value of horizontal tune should be in the range of \( |\nu_x| \approx 0.51 \). At this working point, enhancement of \( \Delta \beta_x/\beta_x \) in HER and LER due to the resonance term in Eqn. 1 would be a factor of 6.7 and 12.8, respectively, compared to the present tune. Without compensation, the large β growth may significantly increase amplitude dependent non-linear aberrations and reduce dynamic aperture and beam lifetime.

More resonance effects are generated by the synchrotron sidebands of the half-integer resonance: \( 2\nu_x + m\nu_y = n \), where \( \nu_x \) is a synchrotron tune, and \( m, n \) are integers. In the LER, where \( \nu_y = 0.025 \), the 1st and 2nd synchro-betatron resonances occur at \( \nu_x = 0.5125 \) and 0.525, while in HER with \( \nu_y = 0.045 \) the 1st sideband is at \( \nu_x = 0.5225 \). Tracking simulations will show that the sidebands have a strong effect on dynamic aperture, therefore working tune should be chosen reasonably far from them. In addition, variation of tune with synchrotron momentum oscillations should be minimized to avoid crossing with these resonances.

Optimization of PEP-II lattice near half-integer resonance and analysis of dynamic aperture are discussed below. The optics with \( \beta_x^*/\beta_y^* = 50/1.25 \) cm at the Interaction Point (IP) is used.

LATTICE OPTIMIZATION

PEP-II has two tuning sections which can be locally adjusted to change betatron tune without affecting the rest of machine optics. Initially, only these sections were modified to move the horizontal tune closer to half-integer, and vertical tune to \( \nu_y \approx 0.61 \) as suggested by beam-beam analysis. But tracking simulations showed that dynamic aperture was not sufficiently large with machine errors and synchrotron momentum oscillations of up to \( \pm 8 \sigma_p \), where \( \sigma_p \) is the rms value of relative momentum spread \( \Delta \nu/\nu \) in the beam. Analysis of chromaticity indicated that non-linear variation of horizontal tune with momentum needs to be

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was chosen between the 1st and 2nd sidebands. Larger, therefore the closest to half-integer working point tune is a factor of 2 smaller while energy spread is 25% smaller, along with the resonances. In the LER, synchrotron working point below the 1st synchrotron sideband without large synchrotron tune, it was possible to place the HER target at half-integer synchrotron sidebands. In HER, a positive linear adjustment of the IR magnet strengths. This small perturbation was compensated by a slight ad-

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The optimized horizontal tune for momentum range of −10σp < Δνx < 10σp is shown in Fig. 2, 3 where the working point is νx/νy = 24.51/23.61 in HER and 38.518/36.61 in LER. The straight dash lines depict the half-integer synchrotron sidebands. In HER, a positive linear chromaticity ξ = +1 was used in Fig. 2 to counteract the negative slope of non-linear tune variation. Due to the large synchrotron tune, it was possible to place the HER working point below the 1st synchrotron sideband without crossing with the resonance lines. In the LER, synchrotron tune is a factor of 2 smaller while energy spread is 25% larger, therefore the closest to half-integer working point was chosen between the 1st and 2nd sidebands.

Minimum of the second order chromaticity was achieved by reducing strengths of the IR sextupoles correcting horizontal chromaticity. Further improvement in LER resulted from reduction of horizontal phase advance between the IR horizontal sextupoles and IP by 5°. For correction of the machine linear chromaticity, strength of the global sextupoles was increased to compensate for the weaker IR sextupoles. Because the adjusted IR sextupoles in HER have a non-zero design orbit, the reduced sextupole strength created a feed-down effect of linear focusing and coupling. This small perturbation was compensated by a slight adjustment of the IR magnet strengths.

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In PEP-II, the most contribution to non-linear chromaticity is generated in the final quadrupole doublets near IP. This chromaticity is compensated by the Interaction Region (IR) sextupoles located in the same phase with the doublets. Variation of strength of these sextupoles allows to compensate quadratic dependence of tune on Δp/p, and a small adjustment of sextupole phase advance helps reduce the higher order variation.

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Secondly, tracking simulations with field errors, misalignment and \( \Delta \beta / \beta = \pm 8 \sigma_p \) synchrotron momentum oscillations were performed for the selected working points. For statistics, ten different settings (“seeds”) of random machine errors were used in each tracking. Perturbation of beam orbit, linear chromaticity, betatron tune and vertical dispersion was compensated using realistic correction schemes in LEGO. Since distortion of \( \beta \) function becomes more sensitive to focusing errors near half-integer resonance, a special correction of \( \Delta \beta / \beta \) was implemented in LEGO. It uses MICADO method to find the most effective quadrupoles to minimize \( \beta \) perturbation.

Due to the greater effect of errors near half-integer resonance, a better machine correction is needed to maintain acceptable dynamic aperture. To verify tolerance to various errors, simulations were performed for different levels of machine correction. It has been confirmed that beam orbit should be decreased for an acceptable dynamic aperture. The better orbit correction reduces the feed-down function be-