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Optimization of Dynamic Aperture of Pep-X Baseline Design*

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Abstract

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OPTIMIZATION OF DYNAMIC APERTURE OF PEP-X BASELINE DESIGN*

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Abstract

SLAC is developing a long-range plan to transfer the evolving scientific programs at SSRL from the SPEAR3 light source to a much higher performing photon source. Storage ring design is one of the possibilities that would be housed in the 2.2-km PEP-II tunnel[1,2]. The design goal of PEPX storage ring is to approach an optimal light source design with horizontal emittance less than 100 pm and vertical emittance of 8 pm to reach the diffraction limit of 1-Å x-ray. The low emittance design requires a lattice with strong focusing leading to high natural chromaticity and therefore to strong sextupoles. The latter caused reduction of dynamic aperture. The dynamic aperture requirement for horizontal injection at injection point is about 10 mm. In order to achieve the desired dynamic aperture the transverse non-linearity of PEP-X is studied. The program LEGO[3] is used to simulate the particle motion. The technique of frequency map is used to analyze the nonlinear behavior. The effect of the non-linearity is tried to minimize at the given constrains of limited space. The details and results of dynamic aperture optimization are discussed in this paper.

INTRODUCTION

PEP-X, is designed to replace 6 arcs of FODO cells of PEPII High Energy Ring (HER) with two arcs of DBA and four arcs of TME and installation of 89.3 m long damping wiggler to achieve an ultra low beam emittance of 0.14 nm-rad (including intra-beam scattering) at 4.5 GeV. In each DBA arc there are 8 DBA super cells. In TME arc there are 32 TME cells. The lattice functions of TME and DBA supercell are shown in Figure 1. In order to reach the small equilibrium emittance of achromatic lattice strong quadrupoles are inevitable to match the optic requirements for small beta functions and dispersion matching between dipoles. Therefore strong sextupoles to correct the natural chromaticity to zero or slightly positive to overcome the transverse head tail instability are needed. However the presence of sextupole means the introduction of nonlinear effects into the design. The nonlinear effects driven by such strong chromatic sextupoles can result in a severely decreased dynamic aperture. Achieving a large dynamic aperture for injection and Touschek beam lifetime becomes challenging for a strongly focusing lattice.

In the process of achieving the desired dynamic aperture for PEP-X baseline design, several guidelines have been applied to minimize the impact of nonlinear effects. The first thing is to optimize the design of the linear lattice to assist in reducing nonlinear behaviour as possible. Phase optimization over a section of lattice is a very effective use to mitigate strong nonlinearities. In a lattice made of n identical cells with $n > 3$ and having a total phase shift of a multiple of 2π, all second order geometrical aberrations will be canceled [4]. The arrangement of the sextupoles is in essence to minimize the strength of the sextupoles by putting sextupoles at the location where the dispersion is large and the beta functions are well separated. The choices of global tunes ν_x, ν_y in the tune diagram are another important factors used to reduce the interaction with the non-linear resonance. A good pair of working tunes should have enough distance away from the major resonance lines in the tune diagram to take into consideration of tune shifts due to the nonlinear effects. Additional sextupole families (geometric sextupoles) located at dispersion free section without affecting the linear chromaticity could be used to further control the nonlinear effects.

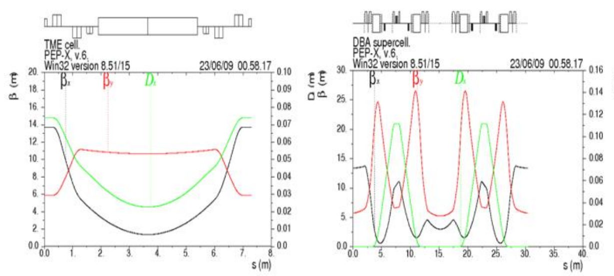

Figure 1: Lattice functions in one TME cell(left) and one DBA supercell(right).

OPTIMIZATION

The linear chromaticity and sextupole correction is given by

$$\xi_{x,y} = \mp \frac{1}{4\pi} \sum_{k=1}^{N} [([(b_2\ell)_k - 2(b_3\ell)_k \eta_{x,y}]\beta_{(x,y),k} \text{ ,}$$

Where $b2\ell$, $b3\ell$ are the integrated quadrupole and sextupole strengths, and β and η are the beta function and dispersion, k indicates the different locations of quadrupoles or sextupoles. The chromaticities of linear lattice are -138.9 and -78.7 of horizontal and vertical respectively. There are four families of sextupoles for chromatic correction. One pair named SD, SF is in the TME cell and the other pair SD1, SF1 is in the DBA cell. All the sextupoles are located at where the dispersion is comparatively large and the beta functions are well separated as shown in Fig .1.

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Optimization phase of unit cell

Both the strengths of nonlinear resonances and tune shift terms depend strongly on the cell tune. Therefore phase advance of unit cell is chosen to cancel or reduce theses terms after a few unit cells [4]. Phase advances in the TME cell are chosen near $\mu_x = 3\pi/4$ and $\mu_y = \pi/4$ which provide nearly I transformations in both planes for every 8 cells to cancel the second order geometric aberrations. Similar to the DBA supercells the optimized values of phase advances are chosen near $\mu_x = 3\pi$ and $\mu_y = \pi$. While the lower order resonance terms are canceled out by symmetry for these cell phase advances, the higher order term like fourth order resonance in the DBA supercells will be amplified. The lattice must be detuned, which will compromise the effects of cancelations to the third order resonance effects. Another reason to detune the cell tune(cell phase advance divided by 2π) away from rational tune is taking into consideration of imperfections of magnet fabrication and engineering tolerances. The imperfections of magnet will introduce higher order magnetic field other than sextupole. Dynamic aperture tracking simulation is used to optimize the phase advance of unit cell. According to the simulation results the phase advances of TME cell are detuned by less than a degree to $\mu_x = (3\pi/4)(1-1/192)$, $\mu_y = \mu_x/3$ and the phase advances of super cell DBA are set to $\mu_x = 3\pi(1 + 1/64)$, $\mu_y = \mu_x/3$.

Sextupole Scheme

The linear chromaticities are corrected to zero by using SD, SF, SD1 and SF1 as shown in Fig. 1. At first the strengths of SD, SF are set to compensate the linear chromaticity of TME cells and SD1, SF1 to compensate the linear chromaticity of DBA cells. However these are found not the best settings. The strengthes of SF1 and SD1 are changed systematically and then SF and SD were used to correct the linear chromaticities to zero. The dynamic aperture tracking is used as the judgement to choose the best setting of sextupole strengths. The final integral strength ($2b_3\ell$) of the four sextupole families are SD: -13.094 m^{-2}, SF: 14.232 m^{-2}, SD1: -12.07 m^{-2} and SF1: 18.2 m^{-2}.

Choice of working point

Unlike the other light source machines adjusting the global tunes usually means to re-optimize all the parameters for the non-linear effects. PEP-X has the advantage to fully utilize the local phase cancelation within the DBA and TME arcs. Then adjust the phase advances in the 6 straight sections through the FODO cells without affecting the local cancelations. The dynamic aperture searching of scan of global tunes by adjusting the quadrupole strengths of FODO cells in the long straight sections are shown in Fig. 2. The horizontal and vertical beam σ shown in the colormap are defined by 100 pm horizontal beam emittance and 50 pm vertical beam emittance at injection point where $\beta_x = 200$ m and $\beta_y = 18.4$ m. From this search the horizontal tune 87.23 and vertical tune 36.14 are chosen.

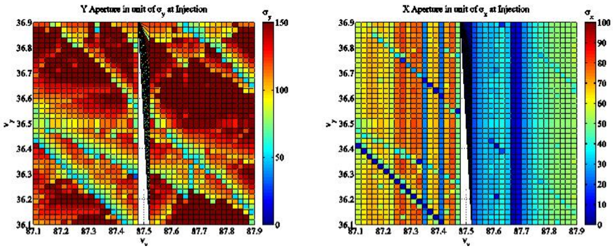

Figure 2: Dynamic aperture scan in tunes space.

Geometric sextupole

However the dynamic aperture tracking using LEGO shows that the horizontal aperture needs to be improved for the aperture requirement for horizontal injection. A tune footprint shows that the horizontal amplitude dependent tune shift is large and causes the shrinkage of the horizontal aperture. A pair of geometric sextupoles SH1, SH2 is placed between the quadrupoles on either side of the ID straights of DBA supercell where dispersion is zero to minimize the amplitude dependent tune shift. The study shows these two sextupoles with the same integral strength of -5 m^{-2} will have the best tune shift amplitude optimization. The coefficients of leading order amplitude dependent tune shift with and without geometric sextupoles are shown in Table 1. Fig. 3 shows the tune shift versus the amplitude. The horizontal tune shift versus amplitude is improved significantly at the price of slight increment of vertical tune shift with amplitude.

Table 1: Coefficient of leading order amplitude dependent tune shift with and w/o geometric sextupoles SH1, SH2.

	$d\nu_x/d\epsilon_x$	$d\nu_y/d\epsilon_y$	$d\nu_y/d\epsilon_x$
with SH1, SH2	-2.41×10^4	-1.10×10^5	3.02×10^4
w/o SH1, SH2	-1.39×10^5	-6.94×10^4	2.86×10^4

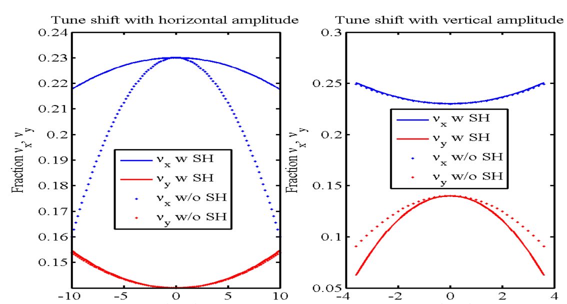

Figure 3: Tune shift with amplitude. The solid lines are tune shift with amplitude with SH1 and SH2. The dots are tune shift with amplitude without SH1, SH2.

DYNAMIC APERTURE

The final dynamic aperture tracking of bare lattice at different energy is shown in Fig. 4, whit the observation point at the injection point. The damping wiggler is included in tracking as pure dipole to provide the necessary damping to achieve the desired small emittance. The nonlinear effect of the damping wiggler is discussed in SLAC report [5]. The horizontal dynamic aperture is sufficient for the horizontal injection. The frequency map of tune footprint at working tune with sextupole setting of zero linear chromaticity is shown in Fig. 5. The diffusion rate is plotted as a colour weighted value. In the tune footprint several resonance lines can be identified like $\nu x - 2\nu y$, $4\nu x$, $2\nu x - 3\nu y$, $2\nu x + 4\nu y$, $6\nu x - 2\nu y$, $9\nu x$.

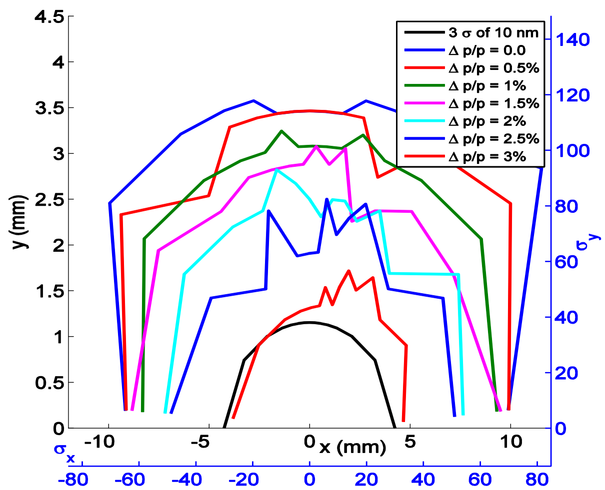

Figure 4: Dynamic aperture tracking of the bare lattice at different energy.

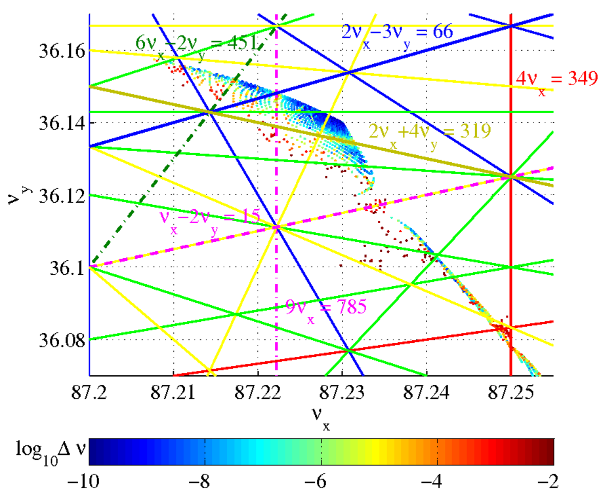

Figure 5: Frequency map of tune footprint. The resonance lines are plotted up to sixth order.

Dynamic Aperture with Errors

PEP-X will inherit as many magnets as applicable from PEP II HER ring. The measured magnetic multipole errors in the magnets of the PEP II HER are used as the magnetic multipole errors [5]. The transverse alignment tolerances and field errors are summarized in Table 2. The alignment error of a magnet is treated individually relative to the designed orbit in this study. Ten random seeds of errors were generated in LEGO. The procedures are first to try to find the closed orbit in the presence of alignment errors and field errors and then applies tune, orbit, chromaticity and coupling corrections to compensate the effects due to the errors including magnetic multipoles , and finally tracks the particles. The resultant dynamic aperture with 4 random seeds of machine errors is shown in Fig. 6.

Table 2: RMS values of transverse alignment tolerances and field errors

	$\Delta x(\mu\text{m})$	$\Delta y\ (\mu\text{m})$	Roll (m rad)	$\Delta B_N/B_N$
Dipole	100	100	0.5	1×10^{-4}
Quad	30	30	0.2	5×10^{-4}
Sext	30	30	0.2	5×10^{-4}

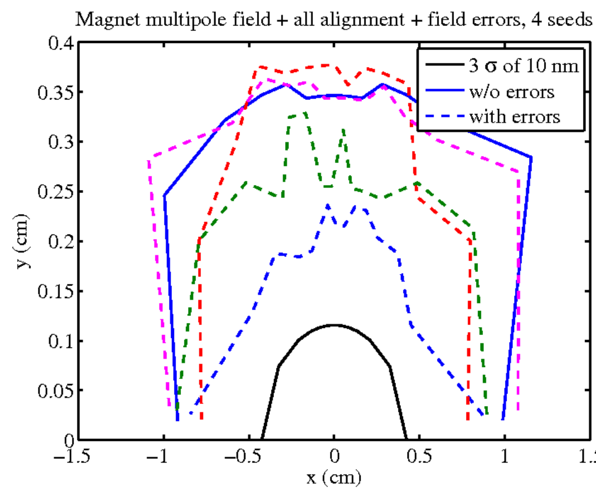

Figure 6: Dynamic aperture for 4 seeds of machine errors for on momentum particle.

DISCUSSION

The dynamic aperture of baseline PEP-X design without errors is sufficient for the horizontal 10 mm injection requirement. With errors a better orbit correction scheme will be needed to find the closed orbit solution for different random seeds. Further optimization with errors of off momentum particle tracking is undergoing.

REFERENCES

[1] R. Hettel et al., “IDEAS FOR A FUTURE PEP-X LIGHT SOURCE”, Proceedings of EPAC08, p. 2031(2008).

[2] R. Hettel et al., “CONCEPTS FOR THE PEP-X LIGHT SOURCE”, Proceedings of PAC09, 2009.

[3] Y. Cai et al., “LEGO**:** A Modular accelerator design code”, Proceedings of PAC97, 1997.

[4] Karl L. Brown, Roger V. Servranckx, “Optics Modules for Circular Accelerator Design”, NIM A258, pp.480-502 (1987).

[5] Y. Cai et al., “A Design Report of the Baseline for PEP-X: an Ultra-Low Emittance Storage Ring”, SLAC-PUB-13999(2010). Also WEPEA073, WEPEA074, this Conference.