DYNAMIC APERTURE AND TOLERANCES FOR PEP-X ULTIMATE STORAGE RING DESIGN*

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Abstract

A lattice for the PEP-X ultimate storage ring light source[1], having 11 pm-rad natural emittance at a beam energy of 4.5 GeV at zero current, using 90 m of damping wiggler and fitting into the existing 2.2-km PEP-II tunnel, has been recently designed[2]. Such a low emittance lattice requires very strong sextupoles for chromaticity correction, which in turn introduce strong non-linear field effects that limit the beam dynamic aperture. In order to maximize the dynamic aperture we choose the cell phases to cancel the third and fourth order geometric resonances in each 8-cell arc. Four families of chromatic sextupoles and six families of geometric (or harmonic) sextupoles are added to correct the chromatic and amplitude-dependent tunes. To find the best settings of the ten sextupole families, we use a Multi-Objective Genetic Optimizer employing `elegant`[3] to optimize the beam lifetime and dynamic aperture simultaneously. Then we evaluate dynamic aperture reduction caused by magnetic field multipole errors, magnet fabrication errors and misalignments. A sufficient dynamic aperture is obtained for injection, as well as workable beam lifetime[2].

INTRODUCTION

Ultimate storage ring design emphasizes reducing the ring emittance towards the diffraction limit of 10-20 keV photons. Such a low emittance lattice is characterized by small beta functions and dispersion, achieved using strong quadrupoles. Strong chromatic sextupoles are consequently needed to correct the natural chromaticity to overcome the transverse head-tail instability. The nonlinear effects driven by such strong chromatic sextupoles can result in a severely reduced dynamic aperture. Achieving a sufficiently large dynamic aperture for injection and adequate Touschek beam lifetime becomes a key issue for a successful ultimate storage ring design.

The nonlinear driving terms up to fourth order in terms of Lie map generated by quadrupoles and sextupoles are:

- Chromatic terms in the third order map: linear chromaticity, second order dispersion, and synchrotron betatron coupling resulting in first order chromatic beta function.
- Geometric driving terms in the third order map: terms driving five different betatron resonances with frequencies $\nu_x,\ 3\nu_x,\ \nu_x-2\nu_y,\ \nu_x+2\nu_y$.
- Chromatic terms in the fourth order map: second order chromaticity and other chromatic terms.
- Geometric driving terms in the fourth order map: three amplitude dependent tune shifts and eight different betatron resonances with frequencies $2\nu_x,\ 4\nu_x,\ 2\nu_y,\ 4\nu_y,\ 2\nu_x-2\nu_y,\ 2\nu_x+2\nu_y$.

These nonlinear driving terms need to be minimized in order to maximize dynamic aperture. In the PEP-X lattice design we choose the cell phases to eliminate all these third order and fourth order geometric betatron resonances driving terms except $2\nu_x-2\nu_y$ in each 8-cell arc[2]. This simplifies dynamic aperture optimization to focus on the remaining amplitude-dependent tune shifts, chromatic tune and the $2\nu_x-2\nu_y$ resonance.

OPTIMIZATION OF DYNAMIC APERTURE

The optimal arrangement of the sextupoles minimizes their strength by locating them in arc where the dispersion is large and the horizontal and vertical beta functions are well separated. There are four families of chromatic sextupoles: SDs at both ends of the TME dipoles, SD1s at the dispersive side of the matching dipoles, SFs and SF1s in the middle of focussing quadrupoles in dispersion regions. Six families of geometric sextupoles are placed at center of quadrupoles in the dispersion-free straights. The schematic layout of the sextupole scheme in arc cell is shown in Fig.1.

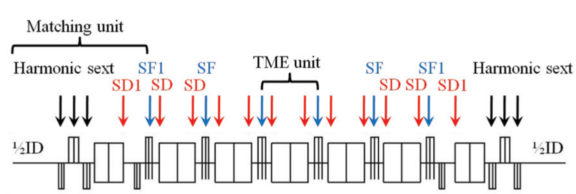

Figure 1: PEP-X 7BA[2] cell sextupole scheme.

We first try to optimize the dynamic aperture without the geometric sextupoles. Fig.2 shows the on- and off-momentum dynamic aperture, tune footprint, amplitude dependent tune and chromatic tune with four families of chromatic sextupoles using the LEGO code[4]. In Fig.2 the large tune footprint implies large amplitude-dependent tune shifts. These are also reflected in the large coefficients of tune shift with amplitude-dependent driving terms[5] as shown in Fig.3. These tune shifts and the $2\nu_x-2\nu_y$ resonance cannot be controlled with only four families of chromatic sextupoles. More sextupole families are needed to correct the tune shift with amplitude terms and other higher order terms.

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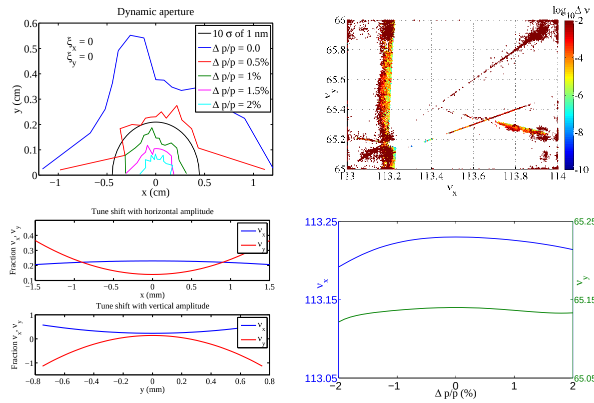

Figure 2: Dynamic aperture (upper left), tune footprint (upper right), amplitude-dependent tune (lower left) and chromatic tune (lower right) without geometric sextupoles.

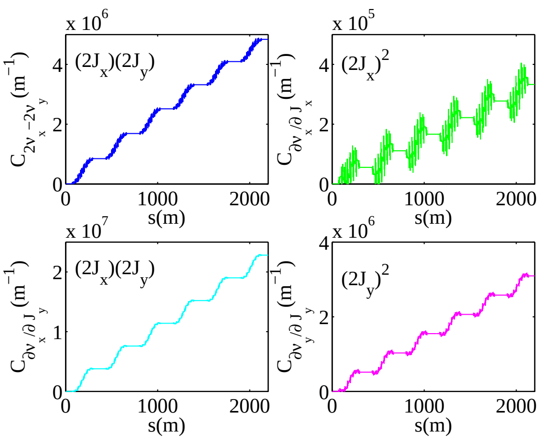

Figure 3: Coefficients of three amplitude-dependent tune shift and the $2\nu_x - 2\nu_y$ betatron resonance driving terms accumulated along the ring without geometric sextupoles.

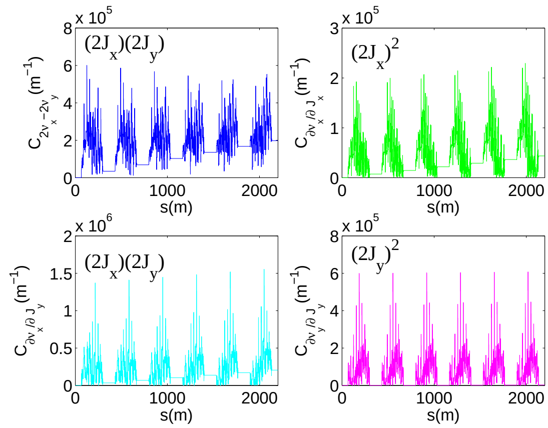

Figure 4: Coefficients of three amplitude-dependent tune shift and $2\nu_x - 2\nu_y$ betatron resonance driving terms accumulated along the ring with geometric sextupoles.

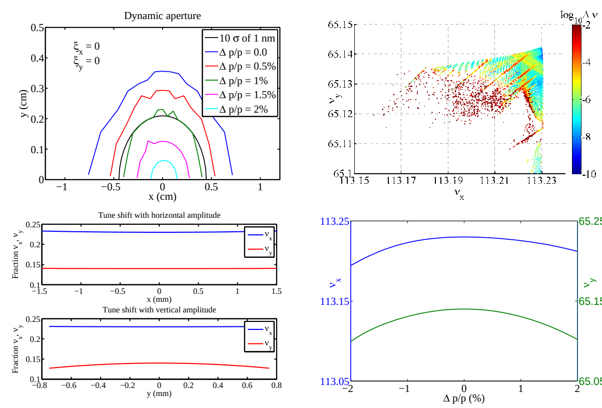

Figure 5: Dynamic aperture (upper left), tune footprint (upper right), amplitude-dependent tune (lower left) and chromatic tune (lower right) with geometric sextupoles.

Tune Shift Corrections

The large amplitude-dependent tune shift is the main cause of the wide tune spread shown in Fig.2. Six families of geometric sextupoles are added to remedy this. These families do not disrupt the cancelation of the geometric resonance driving terms in the arc. Together with the four families of chromatic sextupoles, we can correct the amplitude-dependent tune shifts, chromatic tune to third order, and the $2\nu_x - 2\nu_y$ resonance simultaneously using the accelerator design program OPA[6]. OPA provides interactive optimization of the sextupole Hamiltonian in first and second order. The corrections in OPA are divided into five parts: linear chromaticities and third order geometric terms, chromatic beta functions, higher order chromatic tunes, tune shift with amplitude terms and fourth order geometric terms. In the PEP-X design we correct chromatic tunes, tune shift with amplitude and $2\nu_x - 2\nu_y$ resonance with appropriate weights. The final results of tune shift with amplitude and $2\nu_x - 2\nu_y$ resonance are shown in Fig.4, which are significantly reduced compared with Fig.3. The on- and off-momentum dynamic aperture, tune footprint, amplitude dependent tune and chromatic tune with optimized geometric sextupole settings are shown in Fig.5. The tune footprint and off-momentum aperture shown in the Fig.5 are much improved over that in Fig.2. These imply a better Touschek beam lifetime and magnet error tolerances.

`elegant` *Multi-Objective Genetic Optimization*

To find the best settings of the ten sextupole families, we use a Multi-Objective Genetic Optimizer with `elegant`[3]. The optimization objectives are beam lifetime and the combination of x and y dynamic aperture area. The latter is related to injection efficiency and, to calculate the former, we need to track the local momentum aperture. In tracking of the dynamic and momentum apertures, we include the effects of radiation damping, synchrotron oscillations, physical apertures and machine errors. Machine errors equivalent to 1 % beta beating and 1 % coupling without correction are used in aperture tracking. The up-to-date summary of the optimization results is shown in Fig.6, where the horizontal axis represents aperture and the vertical beam lifetime. The on-momentum horizontal aperture can reach 11 mm and beam lifetime as calculated in `elegant` can be 4 hours (Fig.7). The optimization is still in progress and a complete investigation of solution choices will be reported in the future.

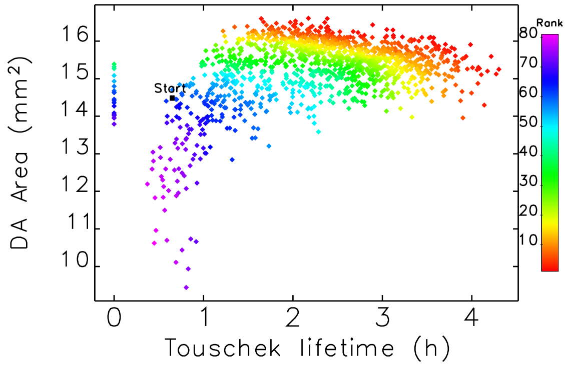

Figure 6: Summary of `elegant` genetic optimization results.

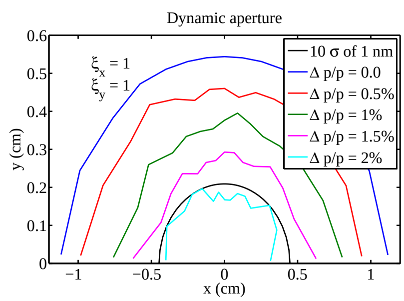

Figure 7: On- and off-momentum dynamic aperture of one of the `elegant` geneticOptimizer code solutions.

EFFECT OF ERRORS

Magnetic field and alignment errors create linear and non-linear optics perturbations which tend to reduce dynamic aperture and lifetime. To maintain acceptable performance, the magnitude of errors must be limited. Furthermore, efficient correction schemes must be implemented to reduce the error effects to an acceptable level. Tracking simulations were performed using the `elegant` [7] and LEGO [4] codes.

In the `elegant` simulations, beam correction was not used. Instead, it was assumed that the corrected lattice will have about 1% beta beat and 1% coupling. The latter were simulated by sufficiently small random quadrupole field and tilt errors. The resultant dynamic aperture for 50 machine settings of random errors is shown in Fig. 8.

LEGO simulations included correction of orbit, beta beat, linear chromaticity and vertical dispersion. An acceptable coupling correction has not yet been implemented into the code, therefore the errors were limited to magnet field errors and horizontal misalignment. In addition, higher order multipole field errors, based on measured PEP-II magnets [8], were used. No errors were applied to beam position monitors, and the linear chromaticity was corrected to +1. Tracking was performed at $\Delta p/p = 0$ for each type of error to determine the aperture reduction.

It was found that magnet random field errors at the level of 10^{-3} reduce aperture only by a few %. Also, the high order multipole field errors based on the PEP-II measured magnets, but applied to smaller bore radius of PEP-X magnets, produced a similar effect. A stronger effect is caused by horizontal misalignments, where the rms errors of 20 μm in quadrupoles, and 50 μm in dipoles and sextupoles reduce aperture by 5–15%.

In the combined error tracking, the rms field errors were set to 10^{-3} in dipoles and quadrupoles and $5 \cdot 10^{-3}$ in sextupoles; and the rms horizontal misalignment was set to 20 μm in quadrupoles and 50 μm in dipoles and sextupoles. The dynamic aperture for 10 random machine settings is shown in Fig. 9. Here, the average dynamic aperture is reduced by $\sim$ 20% and $\sim$ 10% in x and y planes, respectively. The average rms orbit and beta beat after correction are $x_{rms} = 65\mu$m, $(\Delta\beta_x/\beta_x)_{rms} = 5\%$, and $(\Delta\beta_y/\beta_y)_{rms} = 8\%$.

One can see that the results of the `elegant` and LEGO are comparable, with the `elegant` aperture being a little better due to the smaller errors. Future simulations will include coupling effects in order to determine the error effects more accurately.

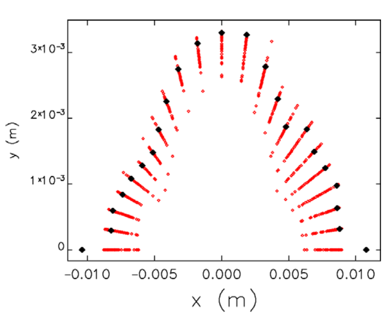

Figure 8: Dynamic aperture in `elegant` simulation for 50 sets of random errors (red) and without errors (black).

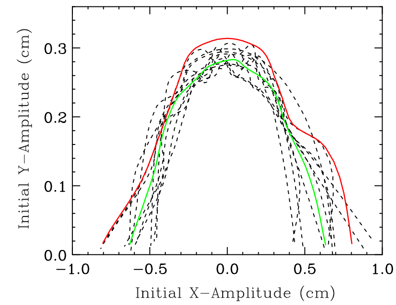

Figure 9: Dynamic aperture in LEGO for 10 sets of random errors (dash), the average aperture (green), and aperture without errors (red).

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