Lattice Design and Optimization for the PEP-X Ultra Low Emittance Storage Ring at SLAC☆

Min-Huey Wang, Yuri Nosochkov, Karl Bane, Yunhai Cai, Robert Hettel, Xiaobiao Huang

SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025

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. One of the possibilities is a new PEP-X 4.5 GeV storage ring that would be housed in the 2.2 km PEP-II tunnel [1, 2]. The PEP-X is designed to produce photon beams having brightness near 10^{22} (ph/s/mm^2/mrad^2/0.1% BW) at 10 keV with 3.5 m undulator at beam current of 1.5 A. This report presents an overview of the PEP-X baseline lattice design and describes the lattice optimization procedures in order to maximize the beam dynamic aperture [3]. The complete report of PEP-X baseline design is published in SLAC report [4].

Keywords: light source, accelerator, brightness, emittance

1. Introduction

One of the design goals of the PEP-X 4.5 GeV light source storage ring is to attain a horizontal emittance of less than 100 pm-rad and vertical emittance of 8 pm-rad in order to reach the diffraction limit of 1-Å X-ray. This should produce a higher brightness than in the other proposed low emittance light source designs as from APS, SPring8, and MAX IV[5, 6, 7]. To reduce the cost of construction, the PEP-X ring is proposed to be housed in the existing PEP-II tunnel. For this reason, the design adopts the same ring

☆Work supported by the Department of Energy under Contract No. DE-AC02-76SF00515.

*Corresponding author mhwang@slac.stanford.edu

geometry with six arcs and six long straight sections as in PEP-II and has the same circumference of 2199.32 m. The design uses hybrid lattice which includes the double bend achromat (DBA) cells in two arcs providing 30 straight sections for insertion devices (ID), the theoretical minimum emittance (TME) cells in the remaining four arcs, and 90 m damping wiggler in a long straight section for the final reduction of horizontal emittance to 86 pm-rad at zero current. Fig. 1 shows schematic of the PEP-X ring layout. The facility would support two experimental halls, each containing 15 ID photon beam lines.

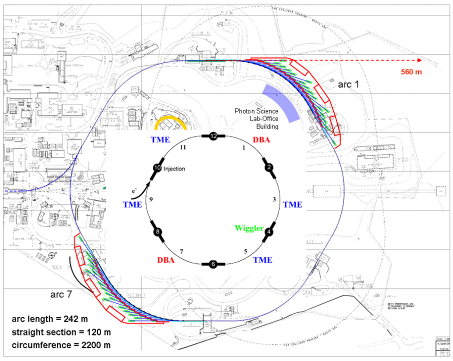

Figure 1: Conceptual PEP-X layout with 2 DBA arcs, 4 TME arcs and 6 straight sections.

2. Lattice Design

The main types of cells used in the PEP-X lattice are DBA, TME and FODO. Each cell type has its special function to help achieving the design goal.

2.1. DBA Supercell

DBA supercells will be used in two of the six arcs in order to provide dispersion free straights for the IDs. Each supercell is composed of two standard DBA cells where one of the two ID straights is adjusted for low β-functions. In total, the 16 DBA supercells in two arcs provide 16 ID straights with $\beta_x/\beta_y = 3.0/6.1$ m and 14 straights with $\beta_x/\beta_y = 16.0/6.3$ m suitable for 3.5 m ID devices. Phase advance in the supercell is optimized to $\mu_x = 3\pi(1 + \frac{1}{64})$, $\mu_y = \mu_x/3$. This provides nearly $-I$ transformation between consecutive supercells which helps to compensate the second order geometric aberrations from DBA sextupoles. The slight phase detuning from $n\pi$ allows to avoid a build-up of higher order resonance driving terms from sextupoles and non-linear field magnet imperfections. Lattice functions of one DBA supercell are shown in Fig. 2.

2.2. TME Cell

The main function of the other four arcs is to minimize the PEP-X emittance while maintaining sufficiently large dynamic aperture and maximizing momentum compaction factor. This is achieved by using a TME cell optics. In general, the TME cell is capable of reaching three times lower emittance than the DBA cell by optimizing β-functions and dispersion in the dipole. Note that the dispersion is not zero in the TME cell, therefore it is not suitable for the IDs. Each of the four TME arcs will contain 32 regular and 2 matching cells. Phase advance in the TME cell is optimized to $\mu_x = (3\pi/4)\,(1 - \frac{1}{192})$, $\mu_y = \mu_x/3$ for the same reasons as for the DBA supercells. Lattice functions of one TME cell are shown in Fig. 2.

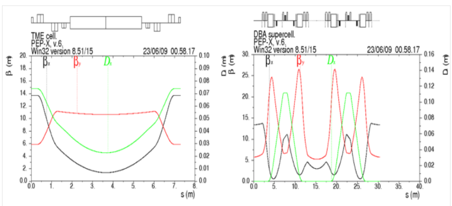

Figure 2: Lattice functions in one TME cell(left) and one DBA supercell(right).

2.3. FODO Cell

The PEP-X has six 123 m long straight sections. Five of them will have identical FODO lattice with 21 quadrupoles per section with average β-function of ≈13 m. They will house the 16 PEP-II RF accelerating cavities, the 90 m long damping wiggler, and the optics systems for betatron tune adjustment and coupling correction. An option of FEL partial lasing in a straight section near the experimental hall is also under study. The last straight section-10 will contain the injection system based on the PEP-II High Energy Ring (HER) design and existing magnets as shown in Fig. 1, but it changes the injection from vertical to horizontal plane.

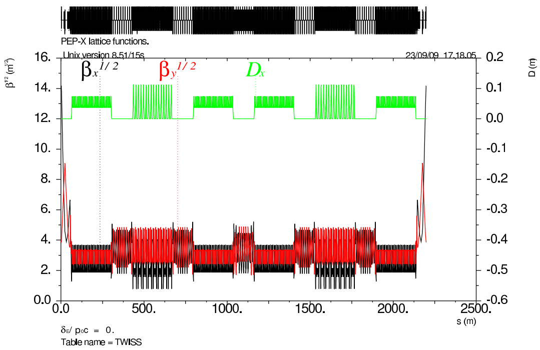

Figure 3: Lattice functions in the complete PEP-X ring starting from injection point.

2.4. Damping Wiggler and Emittance

The PEP-X equilibrium emittance at 4.5 GeV, zero current, and without damping wiggler is 379 pm-rad. The fractional change of emittance due to the damping wiggler can be estimated by the formula in [10] with modification of considering two types of dipoles in PEP-X:

$$\frac{\epsilon_w}{\epsilon_0} = \frac{1 + \frac{4C_q}{15\pi J_x} N_p \frac{<\beta_x>}{\epsilon_0 \rho_w} \gamma^2 \frac{\rho_T \rho_D}{\rho_w (2/3\rho_D + 1/3\rho_T)} \theta_w^3}{1 + \frac{1}{2} N_p \frac{\rho_T \rho_D}{\rho_w (2/3\rho_D + 1/3\rho_T)} \theta_w}, \quad (1)$$

where ϵ_0 is the emittance without damping wiggler, $C_q = 3.83 \cdot 10^{-13}$ m, γ is Lorenz factor, J_x is the horizontal damping partition number, $< \beta_x >$ is the average horizontal beta function in the wiggler, N_p is the number of wiggler periods, ρ_w is the bending radius at the wiggler peak field, ρ_T and ρ_D are the bending radius of TME and DBA cell dipoles respectively, $\theta_w = \lambda_w / 2\pi\rho_w$ is the peak trajectory angle in the wiggler, and λ_w is the wiggler period length. The wiggler efficiency for emittance reduction is determined by the wiggler period length λ_w, the wiggler peak field B_w, and the total wiggler length $L_w = N_p \lambda_w$. The emittance dependence on these parameters had been analyzed and the following optimal values were selected: the total wiggler length of ≈ 90 m, wiggler period of 10 cm and peak field of 1.5 T. This yields a reduction of the zero current emittance to 85.7 pm-rad. However, intra beam scattering (IBS) effects at non-zero current will increase this value. At the PEP-X nominal current of 1.5 A the IBS increases the emittance to 164 pm-rad if the vertical emittance is maintained at the diffraction limited value of 8 pm-rad [4]. Lattice functions of the complete PEP-X ring are shown in Fig. 3 and the main parameters are listed in Table 1.

Table 1: Main parameters of the baseline design for PEP-X.

Energy, E [GeV]	4.5
Circumference, C [m]	2199.3167
Beam current, I [A]	1.5
Horizontal emittance, ϵ_x [pm·rad, 0/1.5 A]	86 / 164
Vertical emittance, ϵ_y [pm·rad]	8
Tunes, $\nu_x/\nu_y/\nu_s$	87.23/36.14/0.0077
Damping times, $\tau_x/\tau_y/\tau_s$ [ms]	20.3 / 21.2 / 10.8
RF frequency, f_{RF} [MHz]	476
Harmonic number, h	3492
Number of bunches, n_b	3154-3422
Bunch length, σ_z [mm]	3.0
Relative energy spread, σ_δ	$1.14 \cdot 10^{-3}$
Momentum compaction, α	$5.81 \cdot 10^{-5}$
Energy loss, U_0[MeV/turn]	3.12
RF voltage, V_{RF} [MV]	8.9
Damping wiggler length [m]	89.3
Length of arc ID straight [m]	4.0
Number of arc ID straights	30

3. Dynamic Aperture Optimization

Attaining a low emittance requires strong quadrupole focusing in the DBA and TME cells. This results in high natural linear chromaticity and the need for strong chromatic sextupoles for compensation. However the latter also generate strong nonlinear effects which can severely decrease the beam dynamic aperture. Therefore, achieving a sufficient dynamic aperture for beam injection and Touschek lifetime in a low emittance lattice becomes increasingly challenging.

The procedure of minimizing the nonlinear effects from the chromatic correction sextupoles and maximizing the PEP-X dynamic aperture consisted of the following steps:

- Choose phase advance in DBA and TME cells yielding a unit (I) linear transfer matrix in both planes for a section made of these cells, where one arc contains integer number of such sections. In such a system the second-order geometrical (on momentum) aberrations will vanish. Since there may be several choices for the phase values, choose the one which minimizes the non-linear chromaticity and maximizes dynamic aperture.

- Fine tune the DBA and TME cell phase advance to minimize the build-up of higher order resonance driving terms.

- Optimize the four families of sextupole strengths in the DBA and TME cells for maximum aperture while keeping the linear chromaticity canceled or slightly positive.

- Optimize the machine betatron tunes in order to minimize the effects of resonances and maximize dynamic aperture.

- Add geometric (harmonic) sextupoles at non-dispersive locations in the DBA supercells for the reduction of amplitude dependent tune shifts and non-linear resonance effects.

Although various analytical and numeric methods can be used for optimization of non-linear sextupole effects (such as MAD HARMON [8]), the result on dynamic aperture in some cases may be distorted by other non-linear effects such as nearby resonance lines. In the above procedure, the sextupole strengths were initially optimized using HARMON and then empirically by direct dynamic aperture tracking using MAD and LEGO codes [9].

One advantage of the PEP-X lattice is that adjustment of the ring betatron tunes does not require re-optimization of the non-linear effects. The latter are to high degree locally compensated within the DBA and TME arcs while the tune is changed using local phase adjustment in the long straight sections without affecting the DBA and TME conditions. The scan of dynamic aperture as a function of the betatron tunes is shown in Fig. 4. The horizontal and vertical beam sizes (σ) shown in the colormap are defined by 100 pm-rad horizontal beam emittance and 50 pm-rad vertical beam emittance at injection point, where $\beta_x = 200$ m and $\beta_y = 18.4$ m. The optimal selected nominal tunes are $(\nu_x,\ \nu_y)$=(87.23, 36.14). The PEP-X DBA supercells include a geometric sextupole at each side of the ID straight, where dispersion is zero. The optimal integral strength for these sextupoles is -5 m^{-2} yielding the maximum dynamic aperture. As shown in Fig. 5, the geometric sextupoles significantly reduce the horizontal tune shift versus amplitude at the cost of slightly higher vertical tune shift.

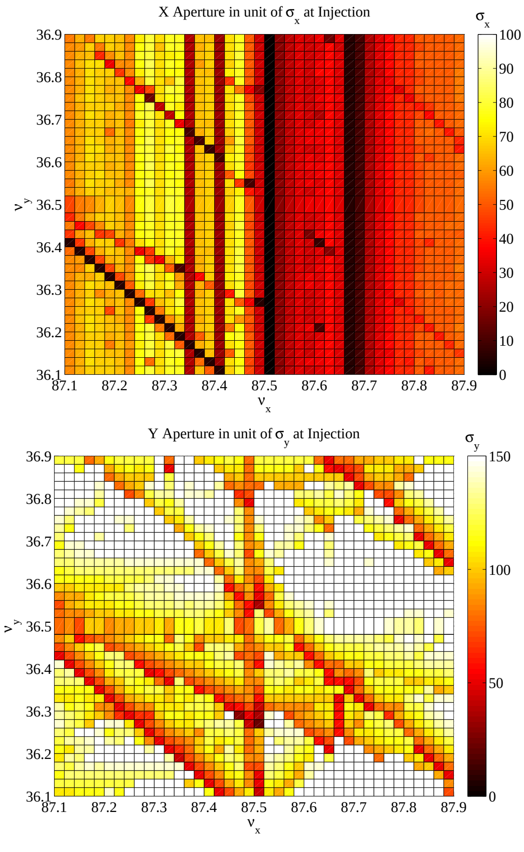

Figure 4: Dynamic aperture scan of betatron tunes. Here $\sigma_x = \sqrt{100 \times 10^{-12} * 200} = 0.14$ mm, $\sigma_y = \sqrt{50 \times 10^{-12} * 18.4} = 0.03$ mm.

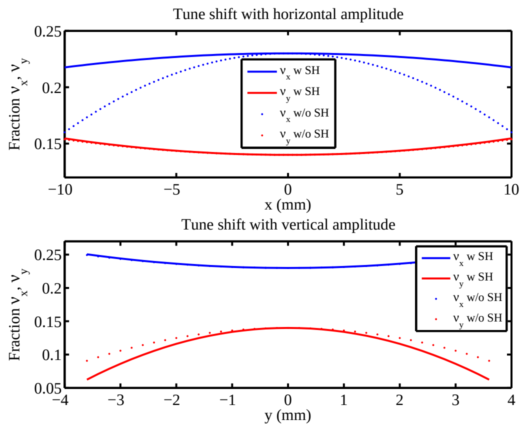

Figure 5: Tune shift versus amplitude: with (solid) and without (dots) geometric sextupoles.

3.1. Dynamic Aperture and Beam Lifetime

PEP-X dynamic aperture at the injection point, without magnet errors, with 90 m damping wiggler, at zero linear chromaticity, and different values of energy deviation is shown in Fig. 6. Since the deformation of RF energy acceptance due to second order momentum compaction is negligible [4], the linear RF bucket momentum of 5.6% is taken as the overall RF momentum acceptance. The latter is larger than the transverse momentum acceptance along the whole ring. Therefore the PEP-X momentum acceptance is determined by the transverse momentum acceptance due to dynamic aperture as shown in Fig. 7.

The PEP-X nominal parameters for intra beam scattering (IBS) calculations are obtained from Table 1. The assumption is that potential well bunch lengthening is not significant and that the nominal current is below the threshold to the microwave instability. Two modes of operation were considered: (1) where the transverse coupling factor κ is adjusted so that the vertical emittance is diffraction limited at 1 $\AA$ (i.e. $\epsilon_y = 8$ pm); this is the more normal mode of operation where PEP-X is a synchrotron light source, and (2) where a round beam ($\kappa = 1$) is chosen, for running an FEL in one of the straight sections. The results of the IBS calculations and Touschek beam lifetime for the two configurations are presented in Table 2, which shows the steady-state values of horizontal and vertical emittance ϵ_x and ϵ_y, energy spread σ_p and bunch length σ_z. It is concluded that for PEP-X, IBS has

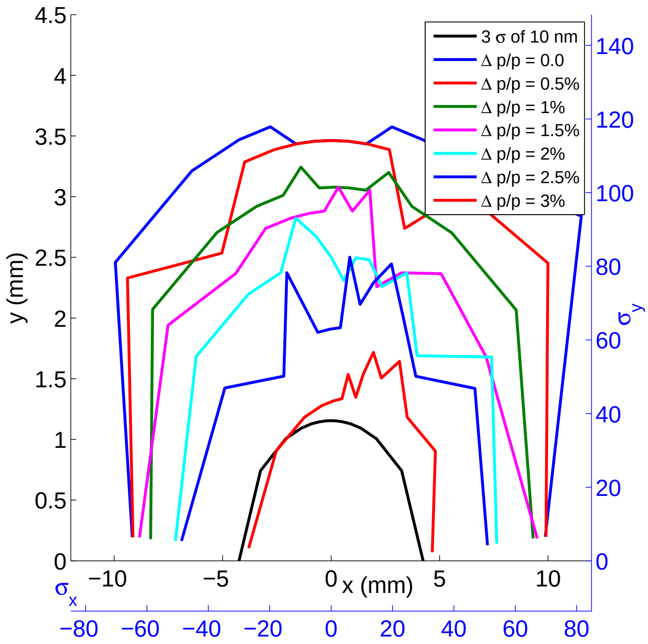

Figure 6: Dynamic aperture of the bare lattice for different energy errors. The σ_x, σ_y are same as in Fig. 4

little effect on σ_p and σ_z. At the normal mode of operation ϵ_x doubles from the nominal case, whereas in the round beam mode it grows by 60%.

Table 2: For flat and round-beam cases at the nominal current $I = 1.5$ A: x-y coupling parameter κ and nominal (zero-current) horizontal emittance ϵ_{x0}; steady-state horizontal ϵ_x and vertical ϵ_y emittances, relative energy spread σ_p, and bunch length σ_z; and Touschek lifetime $\mathcal{T}$. Note that $\epsilon_{x0} = \epsilon_{x00}/(1+\kappa)$ with $\epsilon_{x00} = 86$ pm.

κ	ϵ_{x0} [pm]	ϵ_x [pm]	ϵ_y [pm]	σ_p [10^{-3}]	σ_z [mm]	$\mathcal{T}$ [min]
.049	82.	164.	8.0	1.20	3.16	29.
1.	43.	69.	69.	1.17	3.08	92.

3.2. Effects of Multipole Errors and Damping Wiggler

PEP-X will reuse as many existing magnets from the PEP-II HER as possible. For this reason, the measured multipole field errors in PEP-II magnets were used to simulate the effect on PEP-X dynamic aperture [4].

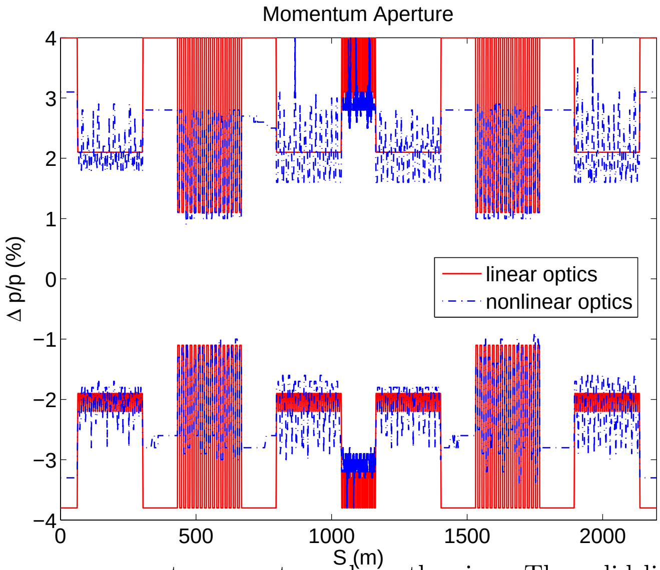

Figure 7: Transverse momentum aperture along the ring. The solid line is the aperture of linear chromatic optics. The dash line is the aperture which includes the nonlinear chromatic effects.

In high periodicity machines insertion of a damping wiggler may break the periodicity and lead to reduction of dynamic aperture. However, the PEP-X lattice has the periodicity of 1 even without the wiggler because the injection straight is different from all other straights. The only global symmetry in PEP-X is the mirror symmetry with respect to injection point. To preserve this symmetry, the damping wiggler is placed in the straight located on the opposite side of the ring relative to the injection point. In addition, phase advance in the wiggler straight is matched to its value without the wiggler to further minimize the impact of the wiggler insertion. For these reasons, the linear effects of the wiggler on dynamic aperture are expected to be minor. However, the wiggler has also a nonlinear field that can potentially affect the aperture.

The wiggler effect on the PEP-X dynamic aperture was studied with the tracking code AT [11]. The thin wiggler poles were replaced by tracking tables. The tracking table is a map of transverse kicks electrons receive from the wiggler as a function of the electron incoming positions. Dynamic aperture for nominal energy and 2% energy error, with and without damping wiggler, with systematic and 10 random sets of multipole field errors are shown in Fig 8. Comparison of the two cases in Fig 8 leads us to conclude that the multipole field errors and the damping wiggler do not cause a large

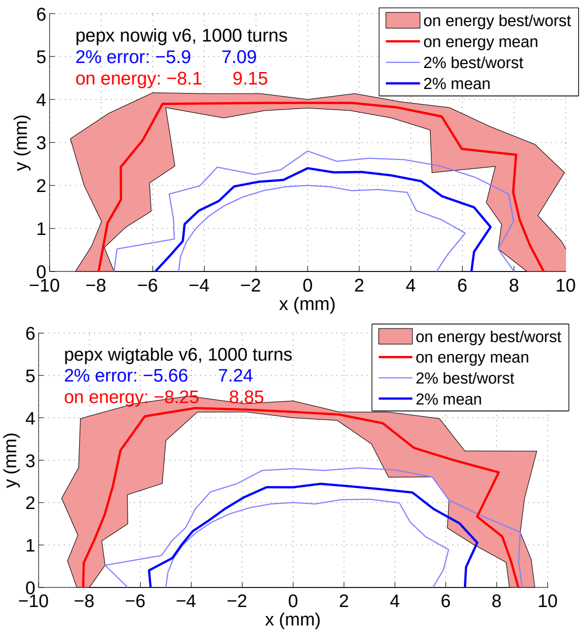

Figure 8: On and off-energy dynamic aperture with multipole field errors. Top: without damping wigglers; bottom: with damping wigglers.

reduction of the PEP-X dynamic aperture.

3.3. Alignment and Main Field Errors

The transverse alignment and main field errors used in the dynamic aperture simulations are similar to the NSLS-II specifications [12]. The resultant dynamic aperture for four random sets of machine errors is shown in Fig. 9. One can see that some combinations of random errors can significantly reduce vertical dynamic aperture, but it is still sufficiently large compared to the beam size. However it is important that the horizontal aperture is not much affected by these errors and remains sufficient for horizontal injection and beam lifetime. More detailed description of the error effects on dynamic aperture and their correction can be found in the SLAC report [4].

4. Conclusion

It is shown that the proposed PEP-X light source lattice in the PEP-II tunnel provides an ultra low emittance value in the range of 0.1 nm-rad at 4.5 GeV with 90 m damping wiggler. The lattice non-linear effects are

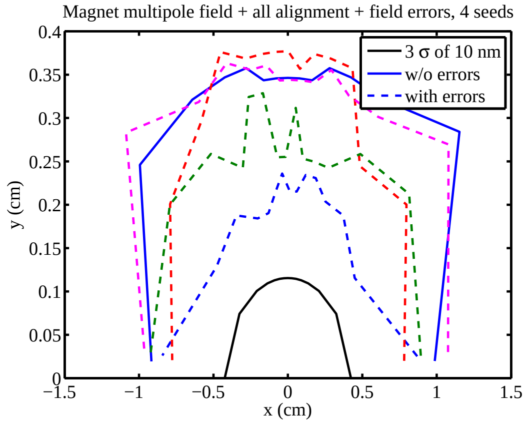

Figure 9: Dynamic aperture of PEP-X with errors. The upper solid line is the aperture of bare lattice.

minimized by the proper choice of cell phase advance, ring betatron tunes and chromatic and geometric sextupole optimization. The ring dynamic aperture is sufficient for horizontal injections and beam lifetime.

References

[1] R. Hettel et al., Proc. EPAC08, p.2031 (2008).

[2] R. Hettel et al., Proc. EPAC09, to be published.

[3] M. H. Wang et al., Proc. IPAC10, p.3437 (2010).

[4] Karl Bane et al., SLAC-PUB-13999 (2010).

[5] M.Borland, Nucl.Instr.andMeth.A557(2005)230;

[6] K.Tsumaki,N.Kumagai,Nucl.Instr.andMeth.A565(2006)394.

[7] "Detailed Design Report on the MAX IV Facility", (http://www.maxlab.lu.se/maxlab/max4/DDR_public/index.html)

[8] H. Grote and F.C. Iselin, CERN/SL/90-13(AP)(Rev. 5).

[9] Y. Cai, *et al.*, "A Modular Accelerator Design Code", SLAC-PUB-7642 (1997).

[10] A. Chao and M. Tigner ed., Handbook of Accelerator Physics and Engineering, World Scientific Publishing (2002), p.189.

[11] A. Terebilo, "Accelerator Modeling with Matlab Accelerator Toolbox", PAC'01, Chicago (2001).

[12] "NSLS-II Conceptual Design Report", http://www.bnl.gov/nsls2/project/CDR/.