DYNAMIC APERTURE STUDIES FOR PETRA III

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Abstract

PETRA III is a low-emittance storage ring dedicated to synchrotron radiation. For efficient injection in the top-up mode, the dynamic aperture has to be larger than 30 mm-mrad in the horizontal plane. This paper presents the choice of tunes and the optimization of the sextupole configuration. Tracking simulations have been performed, including the non-linear effects of 20 four-meters-long damping wigglers and a representative set of undulators. Misalignment and multipole errors are considered as well, leading to specifications for the magnet design and alignment procedure.

INTRODUCTION

The 2.3 km long PETRA storage ring at DESY will be converted into a dedicated light source (PETRA III) with 1 nm-rad beam emittance [1]. One octant will be reconstructed into a DBA structure to accommodate 13-14 insertion devices. The main parameters of PETRA III are listed in Table 1.

For efficient injection in the top-up mode, the required dynamic aperture has to be larger than 30 mm-mrad in the horizontal plane to accommodate the injected beam with 350 nm-rad horizontal emittance. The vertical aperture is limited by the small physical gap (7mm) of the insertion device vacuum chambers inside the DBA octant.

Table 1: Main Parameters of PETRA III.

Parameters	Value	
Energy/GeV	6	
Circumference/m	2304	
Current/mA	100	
Emittance (H./V.)/nm-rad	1.0/0.01	
Number of insertion devices	14	
Number of bunches	960	40

LATTICE DESCRIPTION

The whole ring is composed of one DBA octant and seven FODO achromat octants. The emittance of the bare machine (without damping wigglers) is 4.5 nm-rad, which can be further reduced down to 1 nm-rad with the help of totally 80 meters of damping wigglers, which are located inside two long straight sections. 14 insertion devices, including one 20 meters long undulator, will be installed in the DBA octant. The chromaticity correction is implemented with sextupoles which are located only inside the seven FODO octants because of the small dispersion values inside the DBA octant.

The linear and nonlinear effects of the damping wigglers have been studied carefully [2]. For the linear lattice design damping wigglers and undulators are modelled as linear transfer matrices.

OPTIMIZATION OF SEXTUPOLE CONFIGURATION

Simulation studies show the dynamic aperture to be mainly limited by chromaticity sextupoles located inside the FODO octants. Thus an optimization of the sextupole configuration based on normal form technique [3] has been performed. The basic steps are:

1. Constructing nonlinear one-turn-map in Lie algebra language;
2. Concatenating one-turn-map using BCH theorem and similarity transformation;
3. Using normal form technique to obtain nonlinear coefficients to desired order;
4. Constructing a merit function of sextupoles strength with different weight coefficients to be optimized;
5. Minimizing the merit function of sextupoles strength with nonlinear least squares.

The merit function to be optimized is defined as

$$F(\lambda_m) = w_x\left(K_x(\lambda_{1,2,..,m}) - \xi_x\right)^2 + w_y\left(K_y(\lambda_{1,2,...,m}) - \xi_y\right)^2 + \sum_n w_n\left(K_n(\lambda_{1,2,...,m})\right)^2 + w_{xx}\left(Q_{xx}(\lambda_{1,2,...,m})\right)^2 + w_{xy}\left(Q_{xy}(\lambda_{1,2,...,m})\right)^2 + w_{yy}\left(Q_{yy}(\lambda_{1,2,...,m})\right)^2.$$

Here K_x, K_y are the chromaticities created by sextupoles, $-\xi_x, -\xi_y$ are the natural chromaticities, K_n are the nonlinear coefficients, Q_{xx}, Q_{xy}, Q_{yy} are the coefficients of tune dependence on amplitude, which are second order in sextupoles strength, and w's are the weight factors.

The sequence of sextupoles inside each FODO octant is

5 X (S1 - S2 - S3 - S4).

The optimization result is listed in Table 2. The strength of S1 and S3 are nearly equal, and so are S2 and S4, due to the particular 72 deg phase advance of the FODO cell.

Table 2: Sextupole Strength of Optimization.

Sextupole	K2L (m^{-2})
S1	-0.61940484
S2	0.75713146
S3	-0.65309156
S4	0.78349853

Principally this optimization procedure can be used in an iterative way to re-optimize beta-functions at the sextupoles' location, phase advance between them and machine tunes [4]. In the case of the PETRA III design, the phase advance is chosen as 72 deg per FODO cell, so

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the first order coefficients are cancelled very well. Tune dependence on amplitudes is a second order effect, which usually can be compensated by so-called harmonic sextupoles located at dispersion-free sections. Because each FODO octant in PETRA III contains 20 chromaticity sextupoles, it is very difficult to compensate their nonlinear geometrical effects by few sextupoles located in dispersion-free sections. The attempt of using harmonic sextupoles in PETRA III fails to give a good solution. Table 3 gives the optimization result of using three families of harmonic sextupoles S5, S6 and S7 in the sequence:

S5 - S6 - 5 x (S1 - S2 - S3 - S4) - S7.

The optimized values for harmonic sextupoles are close to zero, which means they are not helpful to enlarge the dynamic aperture. Further investigations show that increasing the number of harmonic sextupoles does not yield better results.

Table 3: Harmonic Sextupole Optimization.

Sextupole	K2L (m^{-2})
S1	-0.62774759
S2	0.75538557
S3	-0.64480679
S4	0.78533184
S5	-0.01954510
S6	0.01404320
S7	0.01168470

SIMULATION RESULTS

The simulation studies were performed with the 6-D tracking code SIXTRACK [5]. Several additional subroutines were inserted into the original code to deal with the tracking of wigglers and insertion devices [6]. The field map of damping wigglers is described by Halbach formulae including several longitudinal harmonic modes. The nonlinear map of damping wigglers is described as a forth order numerical generating function (GF) [7]. The undulators have short period length, so an analytical generating function only including the fundamental mode is accurate enough for the simulation study. It is worthwhile to notice that the tune dependence on amplitude caused by undulators is [8]

$$Q_{yy} = \frac{dQ_y}{dJ_y} \approx \frac{\pi \beta_y^{\,2} L}{4\lambda^2 \rho^2},$$

which requires small vertical beta-function in undulators, specially for very long undulator. Here L is the undulator length, ρ the bending radius, and λ the period length. A low vertical beta-function section was designed to accommodate the 20 meters long undulator in the short straight section North-East [2].

Multipole errors and misalignments of magnets will cause dramatic reduction of dynamic aperture. The influence of those errors on dynamic aperture gives requirements for magnet field quality for the magnet design, manufacture and installation. The existing magnets of PETRA II will be re-used in the seven FODO octants, their multipole errors have been analysed and measured [9]; while for the magnets of the new DBA octant, the field imperfection is obtained by field calculations and the measurement results of the prototypes. The field errors of dipoles and gradient errors of quadrupoles are specified to create ~0.5 mm static orbit distortion and ~10% beta-beat at both planes. The multipole coefficients are summarized in Table 4.

Table 4: Relative multipole coefficients of PETRA III magnets at r = 50mm.

Order	Dipole	Old Quadrupole	New Quadrupole	Sextupole
	1×10^{-4}			1×10^{-3}
1	1.0			
2	0.003	1.0	1.0	
3	2.947	7.45	2.0	1.0
4	1.379	1.75	1.0	1.03
5	3.663	1.60	0.1	2.51
6	2.386	1.51	1.5	0.49
7	1.445	0.43	0.1	0.34
8	6.834	0.34	0.3	0.27
9	3.151	0.43	0.0	3.07
10	3.000	3.23	0.5	0.31

Another reason for dynamic aperture reduction comes from the small physical aperture of undulators. Particles with large horizontal amplitude are scraped by the small vertical physical apertures due to linear and nonlinear coupling effects. Tracking results show most of lost particles are scraped at the location of high-beta undulators, thus additional collimators are needed to protect undulator poles.

Considering all the limitations mentioned above, tune scanning was performed to choose suitable tunes in order to avoid dangerous resonance lines, and at the same time, to obtain large enough energy acceptance (or off-momentum dynamic aperture) to maintain long beam life-time. At present, the tune is chosen as 36.095/31.345. The frequency map including all kinds of errors for one random seed is given in Figure 1. The momentum acceptance is larger than 1.5% which accounts for a Touschek lifetime of 2 hrs at a single bunch intensity of 2.5 mA. Figure 2 shows the dynamic aperture for the ideal machine, machine with errors and the required aperture for high efficient injection. The ideal machine (without multipole errors) has 50 mm-mrad dynamic aperture in the horizontal plane. The reduction of aperture caused by multipole errors, orbit distortion and beta-beat is approximately 30%. Figure 3 displays another frequency map with tune 36.145/31.345, in which case some particles with large amplitude are located on the resonance line $Q_x - 2Q_y = n$.

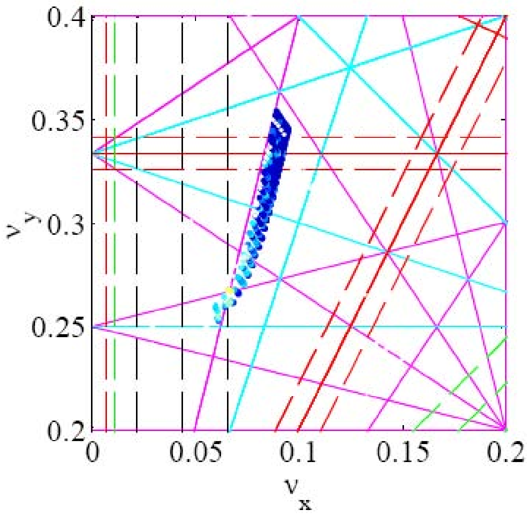

Figure 1: Frequency map with tune (36.095/31.345) including magnet errors (one random seed).

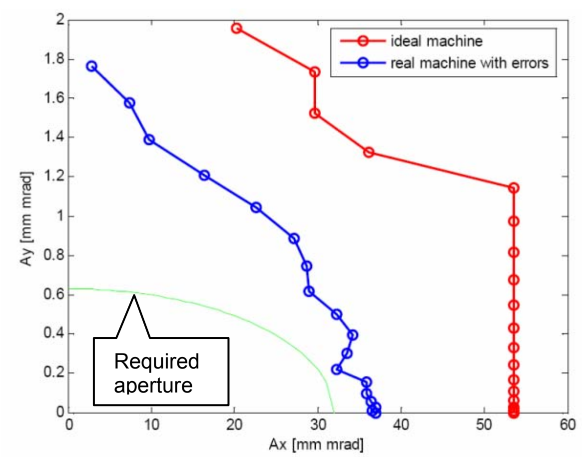

Figure 2: Dynamic aperture of storage ring with and without errors.

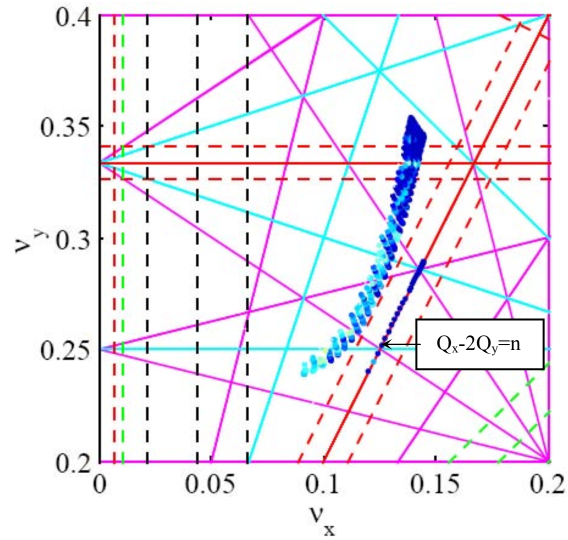

Figure 3: Frequency map with tune (36.145/31.345) including magnet errors (one random seed). Some particles are located on the resonance line $Q_x - 2Q_y = n$.

SUMMARY

The dynamic aperture of PETRA III has been calculated and optimized. Tune scanning has been performed to choose suitable tunes to maintain large enough dynamic aperture and energy acceptance. Simulation results show that the lattice design, magnet misalignments and error specifications can satisfy top-up injection requirements.

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