Chromaticity Compensation and Dynamic Aperture Limitation of SIBERIA-2

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Abstract

Nonlinear beam dynamics studies of the 2.5 GeV dedicated SR source SIBERIA-2 are described. The effect of chromatic sextupoles and measured multipole field errors are taken into account. The influence of high order resonances is considered. The technique for finding the alternative operation point with an extended nonlinear stable region is described.

I. INTRODUCTION

The dedicated SR source SIBERIA-2 [1] is intended for experiments with photon beams of high brightness from both dipoles and insertion devices. The requirements for horizontal emittance minimization together with the matching of lattice functions in the insertion device regions determine the lattice quite unambiguously [2]. The intrinsic feature of low-emittance lattices is rather large chromatic aberrations due to the strong horizontal focusing needed to achieve the minimal emittance.
To compensate the chromatisity, strong sextupoles are in use. Due to the presence of sextupoles the nonlinear effects become of great importance for the transverse particle motion and nonlinear perturbation may lead to a severe reduction of dynamic aperture and beam lifetime limitation.

II. NATURAL CHROMATICITY COMPENSATION

SIBERIA-2 has a six fold symmetry lattice with 12 three meter long straight sections to accommodate insertion devices, rf and injection equipment. The horizontal emittance at 2.5 GeV is equal to $\varepsilon_x = 76$ nm-rad. Fig. 1 shows one half of the cell together with the optical functions for the operation point $\nu_x = 7.717$ and $\nu_z = 7.694$. For this mode the produced natural chromaticities are equal to $\xi_x = -23.9$ and $\xi_z = -23.8$.
Two families of chromatic sextupoles are introduced in the dispersive straight section in a way to conserve both lattice symmetry and cell mirror symmetry.

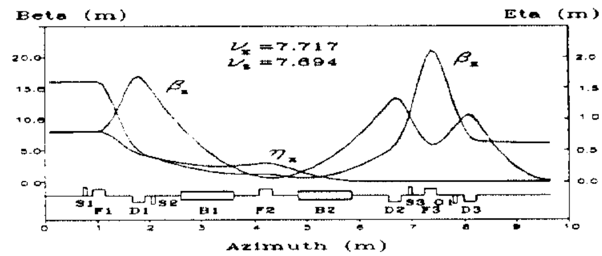

Figure 1: Schematic desing of one half of SIBERIA-2 cell and the optical function

The betatron tune region was chosen far from the sextupole structure resonances $3\nu_x = 24$, $\nu_x + 2\nu_z = 24$, $-\nu_x + 2\nu_z = 6$, as well as the resonances $\nu_x = 7.5$ and 8. The other first order sextupole resonances which are closer to the working point are suppressed due to the lattice symmetry.
Fig. 2 illustrates the dependences of the tunes and lattice functions at the cell middle point on the momentum deviation while the linear chromaticities are corrected.

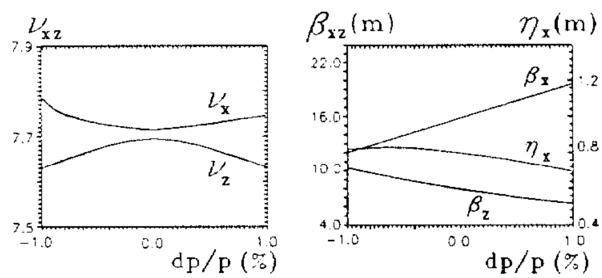

Figure 2: The dependences of the tunes and optical functions on momentum deviation with corrected chromaticity

III. REQUIRED APERTURE

The required aperture was estimated bearing in mind:
i) *Injection efficiency.* The 450 MeV electrons will be injected in one turn into the horizontal phase space using a bump orbit which is produced by a nanosecond kicker and a prekicker [3]. Taking into account the injected beam

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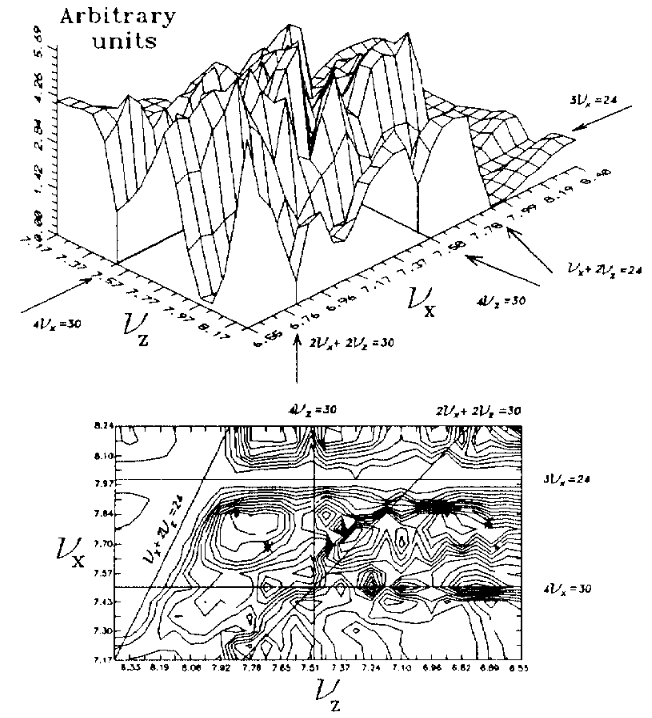

Figure 3: Dynamic aperture versus betatron tunes

emittance, septum leak field, injection orbit errors, etc. the required aperture is 2.6 cm in horizontal direction. The vertical aperture is determined by the injected beam emittance and should not be less than ± 0.8 cm.
ii) *Beam lifetime.* For SR experiments with high time resolution the single bunch operation mode is required. The computation results have shown that for the $\sim 0.1-A$-single bunch the beam lifetime is determined by Touschek effect in the whole energy range of SIBERIA-2. To provide good lifetime at 2.5 GeV with 0.1 A electron current, average pressure ≤ 2 nTorr and betatron oscillations coupling $\varepsilon_z = 0.01\varepsilon_x$ the following aperture sizes are needed: $A_x = \pm 2.4$cm, $A_z = \pm 1.3$cm (the possible rms closed orbit errors $\sigma_{x,z} = \pm 0.3$ cm were included into consideration). The vacuum chamber and the "good" field area in dipoles and quadrupoles do not restrict the aperture size.

IV. Tracking

The simulation has been carried out using the FORTRAN 77 code MAcSim, developed by the authors [4] and run on MicroVAX-3.500 under VAX/VMS-5.2. As is standard, the code is double precision.
The code tracks the particles through the sequence of magnet elements in finite-length or thin-length approximation. To economize the CPU time for the linear part of the lattice the matrices are prepared before tracking and the structure is composed into a block structure. For finite length nonlinearity the 4-order Runge-Kutta integration is used while for thin element a nonlinear kick is performed. Systematic and/or random multipole errors can be introduced in any element.
At each turn, phase coordinates are accumulated. After the tracking performed, the graphics or other outputs can be done in any canonical variables set: $J-\psi$, $x-p$ or $x-z$.
Options include: spectral analysis, the computation of the amplitude dependent tune shift, harmonic correction, distortion functions, Courant-Snyder invariant deviation, etc.

V. Tracking results

A. Operation point

In order to test the sensitivity of the lattice to the operation point, the dependence of the dynamic aperture on betatron tunes was investigated. The tunes were changed by the quadrupoles in nondispersive straight section in the ranges: $\nu_x = 7.15 \div 8.25$ and $\nu_z = 6.55 \div 8.35$ with the step equal to $\Delta\nu = 0.05$. After the linear chromaticity correction, the dynamic aperture was calculated for 500 revolutions in each point.
To have a convenient figure of merrit, which combines horizontal and vertical dimensions of the dynamic aperture and its shape, in a boundary curve $A_z = f(A_x)$ an ellipse whose area as large as possible was inscribed. Then the only quantity (ellipse area S_m) characterizes the aperture "quality". This criterion allowes us to avoid apertures which are large, but irregular in shape.
The results of the simulation are demonstrated in Fig. 3. The following structure sextupole resonances are close to the initial operation point $\nu_x = 7.717, \nu_z = 7.694$:
$3\nu_x = 24$, $\nu_x + 2\nu_z = 24$ (first order);
$4\nu_x = 30$, $2\nu_x + 2\nu_z = 30$, $4\nu_x = 30$ (second order).
The most powerful among them are $3\nu_x = 24$ and $\nu_x + 2\nu_z = 24$: in our case, strong nonlinenear coupling is present in transverse motion.
Fig. 4 illustrates the dynamic aperture for the initial operation point ($S_m \simeq 3.6$, arbitrary units). The alternative operation point $\nu_x = 7.763, \nu_z = 6.698$ was chosen to increase the dynamic aperture: at this point $S_m \simeq 9.5$ whereas the parameters which determined the machine performance (emittance, amplitude functions, etc.) are almost the same.

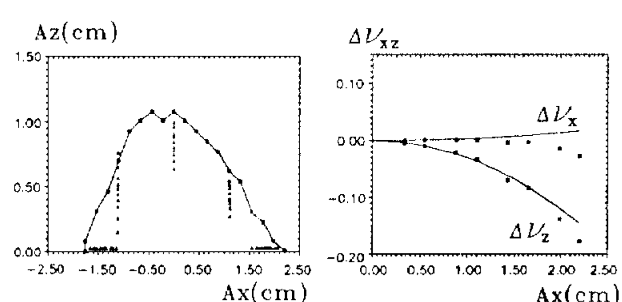

Figure 4: Dynamic aperture without/with multipole errors and amplitude dependent tune shift (initial point).

B. Tracking at the initial operation point

Phase trajectories for the initial operation point in $J_x - \psi_x$ space are shown in Fig. 5. These plots are taken in the middle of the nondispersive straight section, where $\alpha_{x,z} = 0$.
Near the limit of the stable area ($A_x \simeq 2.4$cm) one can see

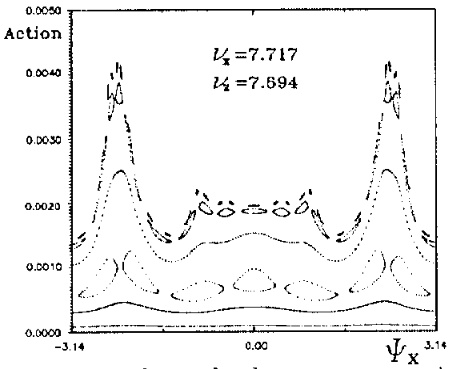

Figure 5: Horizontal phase space trajectories (initial point).

the resonances $18\nu_x = 138$ and $29\nu_x = 222$ (the last looks like the island chain in the stochastic region). At $A_x \simeq 1.4$ cm there is strong enough (the width ΔJ_x is large) resonance $7\nu_x = 54$. In spite of the fact that this resonance is isolated by invariant surfaces, these surfaces can expect to be destroyed due to the breaking of the lattice symmetry (for example, by the multipole errors) and the stable area limit will be shrinked.
The distortion of the invariant curves is explained by the combined effect of the resonances $3\nu_x = 24$ and $4\nu_x = 30$. The vertical plane tracking was plotted as well and the nonlinear coupling effects were investigated.
Fig. 4 plots the tune versus the amplitudes obtained by tracking and calculated according to the second order perturbation theory. The discrepancy between them suggests that the higher orders should be taken into account.
To find the influence of multipole errors on the dynamic aperture the tracking for 10 lattices with systematic and random multipole errors was performed. The results of magnetic mapping of the lattice elements provide us with the errors amplitudes.
The plot of tracking results in Fig. 4 shows the shrinking of the stable area. It is worth noting that the resonance $7\nu_x = 54$ has an essential effect on the dynamic aperture limitation in horizontal plane.

C. Alternative Operation Point

The following conditions were taken into account to chose alternative tunes:
i) the experimental capability of the machine, which depends on such parameters as emittance, lattice functions, etc., should not be restricted;
ii) the dynamic aperture has to be increased;
iii) the sensitivity of the lattice to multipole errors should reduce.

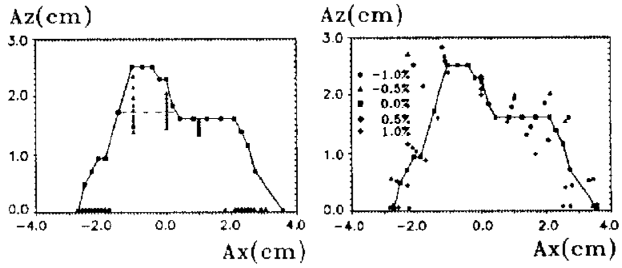

Figure 6: Dynamic aperture without/with multipole errors and momentum dependence of the dynamic aperture for the alternative point.

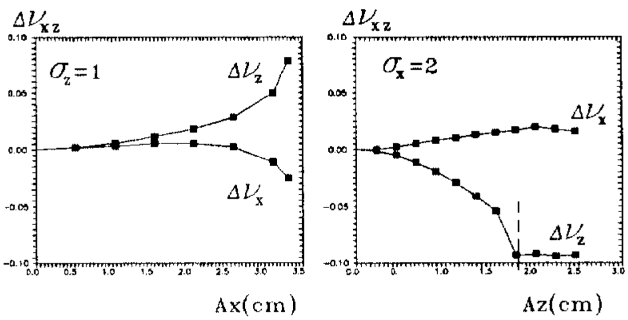

Figure 7: Amplitude dependent tune shift (alternative point).

From the above, $\nu_x = 7.763$ and $\nu_z = 6.698$ were chosen as the tune values for the alternative point. The dynamic aperture with/without multipole errors for the detuned version is given in Fig. 6, the amplitude dependent tune shifts are depicted in Fig. 7. The motion behind the dashed line in both Figures cannot be considered as unambiguously stable, because the studies evidence that this region ($A_z \geq 1.8$cm) is inside the resonance $2\nu_z - \nu_x = 6$ and any symmetry break will distort the stability.
The horizontal phase curves demonstrate the absence of strong resonances inside the aperture. Fig. 6 gives the numerical results for the off-momentum particle at $\pm 1\%$ momentum deviation for the alternative operation point.

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