DYNAMIC APERTURE OPTIMIZATION OF THE NICA COLLIDER*

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Abstract

NICA is a proton and heavy ion collider being built at JINR in Dubna, Russia. It was shown that nonlinear quadrupole fringe fields are among the main factors limiting dynamic aperture of the machine. In the present paper the following ways of dynamic aperture optimization were studied: betatron tunes optimization and placing octupole lenses to the lattice to compensate fringe fields' effect.

INTRODUCTION

Dynamic aperture (DA) optimization study for NICA lattice was started recently using the program codes MAD-X [1] and TrackKing [2]. At the moment the only nonlinearities taken into account are chromatic correction sextupoles, quadrupole nonlinear fringe fields in hard edge approximation [3] and octupoles added to compensate the latter effect. Figure 1 shows that DA is limited mainly by fringe fields of central lenses of final focus (FF) triplets (quads 2), contribution of the other triplet's lenses (quads 1, 3) is also significant. Additional DA reduction due to fringe fields of arc quadrupoles is negligible. Resulting

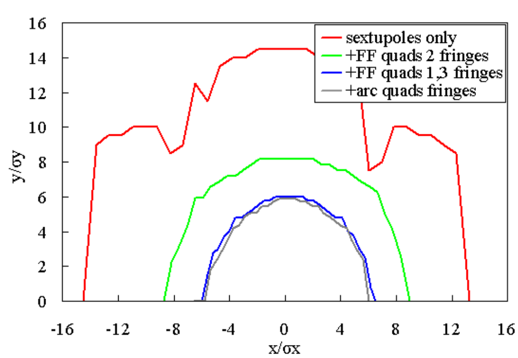

Figure 1: Effect of quadrupole nonlinear fringe fields on DA.

DA size is inacceptably small, therefore, optimization is necessary. In theoretical part of the present paper the relationship between quadrupole nonlinear fringe fields and octupole fields is shown. Then two steps of optimization are described. Firstly, we place two families of thin octupoles into the chromatic correction sextupoles and insert a "phase trombone" into the lattice (fictitious thin linear element which adjusts betatron tunes to the given values). Then we try to maximize DA with these octupoles and find the region of betatron working points where DA gain is the most significant. At the second stage we rematch the linear lattice using MAD-X to decrease influence of nonlinear fringe fields and bring working point to the previously defined region, then DA is optimized again with octupoles. Finally we make some estimations to prove that resulting increased DA is stable in the presence of magnetic field errors and misalignments.

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NONLINEAR QUADRUPOLE FRINGE FIELDS AND OCTUPOLES

Hamiltonian for charged particle moving in a lattice with quadrupole and octupole fields can be written as follows

$$H = \frac{{p_x}^2+{p_y}^2}{2} + k_1(s)\frac{x^2-y^2}{2} + p_x k_1'(s)\frac{x^3+3xy^2}{12} - \\ -p_y k_1'(s)\frac{y^3+3yx^2}{12} + k_3(s)\frac{x^4-6x^2y^2+y^4}{24} . \qquad (1)$$

Here quadrupole gradient k_1' is introduced to take into account nonlinear quadrupole fringe fields.

If all octupoles are thin, then each of them causes the following coordinate transformation

$$\begin{aligned} (\bar{p}_x)_{\rm oct} &= p_x - (k_3 l)\frac{x^3-3xy^2}{6} \\ (\bar{p}_y)_{\rm oct} &= p_y - (k_3 l)\frac{y^3-3yx^2}{6} \end{aligned} , \qquad (2)$$

where l is effective octupole length. If we also consider edges of each quadrupole as thin elements (so called "hard edge approximation" [3]), then the coordinate transformation for quadrupole fringe can be obtained

$$\begin{aligned} (\bar{x})_{\rm fringe} &= x + \Delta k_1 \frac{x^3+3xy^2}{12} \\ (\bar{y})_{\rm fringe} &= y - \Delta k_1 \frac{y^3+3yx^2}{12} \\ (\bar{p}_x)_{\rm fringe} &= \frac{p_x\left(1-\Delta k_1\frac{x^2+y^2}{4}\right)+p_y\Delta k_1\frac{xy}{2}}{1-(\Delta k_1)^2\frac{(x^2-y^2)^2}{16}} \\ (\bar{p}_y)_{\rm fringe} &= \frac{p_y\left(1+\Delta k_1\frac{x^2+y^2}{4}\right)-p_x\Delta k_1\frac{xy}{2}}{1-(\Delta k_1)^2\frac{(x^2-y^2)^2}{16}} \end{aligned} , \qquad (3)$$

where Δk_1 is a variation of the quadrupole gradient, it has opposite signs at entrance and exit faces of the quadrupole. One can see that $\Delta(\bar{p}_{x,y})_{\rm oct}$ and $\Delta(\bar{x}, \bar{y})_{\rm fringe}$ have similar structure but with different signs between terms. Therefore, nonlinear quadrupole fringe can be called "quasi-octupole".

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There is no obvious way to improve DA, even if the sort of nonlinearities is clearly defined. One possible technique is to flatten betatron tune-amplitude dependence up to large enough apertures, because if this dependence is strong, it can limit DA by driving tunes to strong resonances. In the case of thin octupoles and quadrupole edges the following amplitude-dependent tune shifts can be obtained [4]

$$\begin{aligned}\Delta Q_x \approx \frac{1}{16\pi}\sum_o (k_{3,o}l_o)\left(\beta_{x,o}^2 I_x - 2\beta_{x,o}\beta_{y,o}I_y\right) + \\ +\frac{1}{8\pi}\sum_q (k_{1,q}l_q)k_{1,q}\left(\beta_{x,q}^2 I_x + 2\beta_{x,q}\beta_{y,q}I_y\right) \\ \Delta Q_y \approx \frac{1}{16\pi}\sum_o (k_{3,o}l_o)\left(\beta_{y,o}^2 I_y - 2\beta_{x,o}\beta_{y,o}I_x\right) + \\ +\frac{1}{8\pi}\sum_q (k_{1,q}l_q)k_{1,q}\left(\beta_{y,q}^2 I_y + 2\beta_{x,q}\beta_{y,q}I_x\right)\end{aligned}, \tag{4}$$

where summation is performed over octupoles and quadrupoles. With proper choice of octupole strenghts these terms can cancel each other exactly, but DA may be not optimal in this case because of higher order terms coming from quadrupole fringe fields. So, direct comparison of tune-amplitude plots is needed to determine optimal degree of cancellation, this can be performed using TrackKing.

WORKING POINT AND OCTUPOLE OPTIMIZATION

It is believed that working point of heavy particle collider should be near coupling resonance $Q_x = Q_y$ to keep beams round. Therefore, tune scan can be performed only in one dimension along this resonance. Results of this scan are shown in Fig. 2, they do not change with small deviations from the resonance with amplitude of $|Q_x - Q_y| < 0.01$. As we can see, DA can be improved

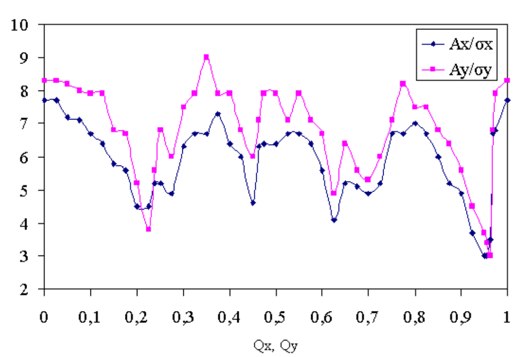

Figure 2: DA tune scan along the coupling resonance.

by shifting working point down, towards sextupole resonance, which is suppressed by octupole-like terms. New working point will be $Q_x/Q_y = 0.361/0.364$. It improves initial DA to $7.5\sigma_x \times 9\sigma_y$. Then optimal octupole strengths should be found. We have x- and y-family of octupoles, so we can optimise x-family first, because pure horizontal motion does not disturb vertical one, then optimize y-family. Tune-amplitude dependence for different octupole strengths in these two steps is shown in Fig. 3 and Fig. 4. Optimal octupole configuration is $k_{3,x}l = -9\ \mathrm{m}^{-2}$, $k_{3,y}l = -10\ \mathrm{m}^{-2}$.

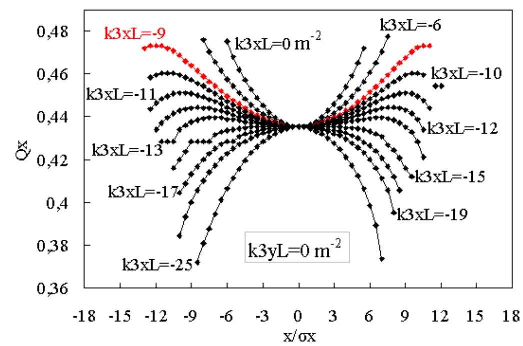

Figure 3: Tune-amplitude dependence for different strength of x-octupoles.

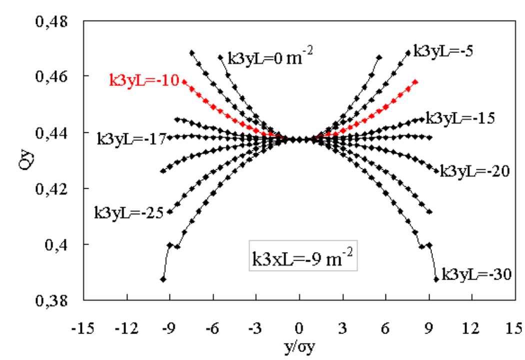

Figure 4: Tune-amplitude dependence for different strength of y-octupoles.

LATTICE OPTIMIZATION

According to (4), tune shifts depend quadratically on the quadrupole strenghts and beta-function values in them. So, the idea is to reduce $\beta_{\max}$ by adjusting straight section quadrupoles providing that their strenghts will be increased insignificantly or even reduced. Also working point should be brought to $Q_{x,y} = 0.39$.

Initial optical functions of NICA are presented in Fig. 5. Optical functions of interaction region in initial (dashed lines) and modified (solid lines) lattice of NICA are presented in Fig. 6. $\beta_{\max}$ in central quadrupole of the final focus triplet is reduced from 250 m to 200 m. Figure 7 shows DA before and after octupole optimization for both lattices.

MISALIGNMENTS AND FIELD ERRORS

Dynamic aperture shown in Fig. 7 is for ideal case. It will degrade due to magnetic field errors of the lattice el-

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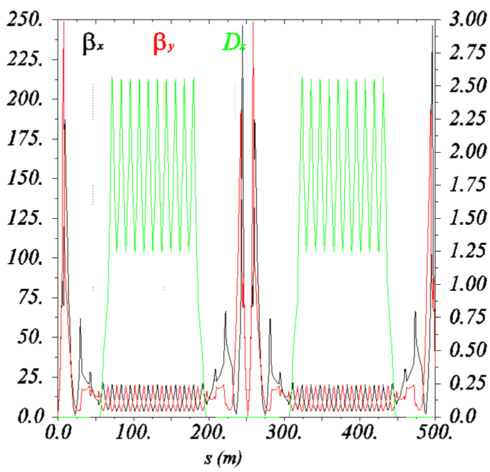

Figure 5: Optical functions of NICA (initial lattice).

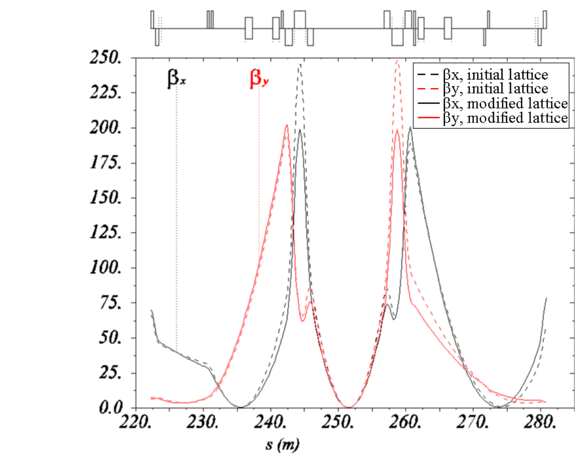

Figure 6: Optical functions of interaction region of NICA.

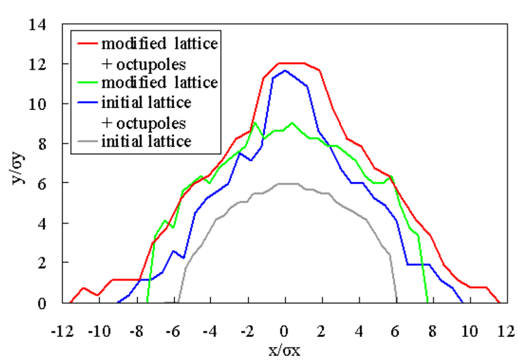

Figure 7: DA for initial and modified lattice before and after octupole correction.

ements. An attempt to estimate this effect was made in the case of pure octupole error in all quadrupoles. Integral strength of the octupole perturbation was 10^{-4} of the quadrupole gradient integral at $r = 3$ cm. Error distribution was Gaussian with a cut at 2σ. Misalignments of the beamline elements are another source of dynamic aperture degradation. Only effect of sextupoles and octupoles displacement can be estimated at the moment, because closed orbit correction module in TrackKing is still under development. Figure 8 shows DA for 10 different random seeds with octupole gradient errors in quadrupoles and transversal multipole displacements for initial and modified lattice. Misalignment distribution was Gaussian with $\sigma = 0.1$ mm and a cut at 2σ. One can see that assigned field errors and

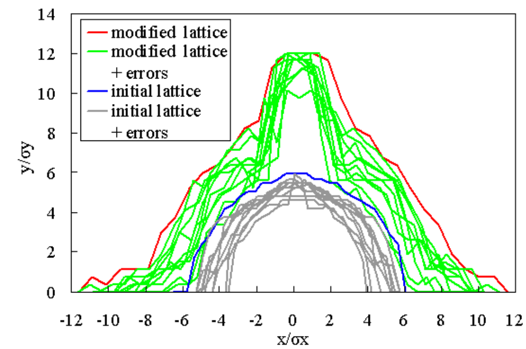

Figure 8: DA degradation due to octupole field errors in quadrupoles and multipole misalignments.

misalignments have reduced DA of modified lattice to that of initial one, whereas initial DA would be reduced to less than $4\sigma_x \times 4\sigma_y$.

FUTURE PLANS

Other factors affecting beam dynamics in NICA are intrabeam scattering and space charge effect. Simulation of these effects will be implemented in TrackKing soon. Also an attempt will be made to develop fast enough symplectic algorithm for simulation of the longitudinal kick due to space charge as well as transversal one. Closed orbit correction module also will be implemented soon, then more realistic simulation of misalignments will be available.

CONCLUSION

Simulations with MAD-X and TrackKing show that nonlinear fringe fields of FF triplet quadrupoles reduce DA of the NICA collider to $< 6\sigma$. Octupolar field errors and misalignments of chromatic correction sextupoles may reduce it further to $< 4\sigma$. Therefore, various sorts of optimization are to be done. Firstly, linear lattice should be modified to reduce strength of FF quadrupoles and beta-functions in them. Secondly, this is working point optimization, another question to answer is how far should it be from coupling resonance. And finally optimal octupole field distribution along the lattice should be found to compensate quasi-octupolar fields coming from quadrupole fringe fields.

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