The Single Beam Dynamics Study at CESR [1]

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Abstract

The described in [1] nonlinear field components of CESR elements have been included in model structure. Then using program MAD [2] the single beam dynamics was explored. The calculated variation of betatron tunes versus orbit position and the excitation of the nonlinear betatron resonances found with tracking are in good agreement with measurements. The elements given the main contribution into tune variation as well as into the nonlinear coupling resonances excitation have been detected.

Model Nonlinearities

The CESR nonlinear field components included in model have been described in [1]. The effective nonlinearity of a element was represented by thin multipole placed in structure next after it. In the case of quads, sextupoles and horizontal separators the strength of these multipoles was proportional to the main element strength. The nonlinearity of vertical steerings was incorporeted into mode as the following. First, using the save set data and vertical steerings calibration, its deflection angles have been calculated, then its nonlinearities were determined according to magnetic measurements. The

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corresponding multipoles were placed in model structure in the location of these steerings.

Below is the list of expressions used for the calculation of the nonlinear magnetic field components of the different types of CESR elements. It is based on the data described in [1] and is given in the form of MAD definition.

- Quads. The table below is the summary of coefficients used for calculation of quads mutipoles strength.

Quad type	$K2L/K1L[1/m]$	$K5L/K1L\,[1/m^4]$	$K9L/K1L\,[1/m^8]$
REC West	$1.752 \cdot 10^{-3}$	$1.090 \cdot 10^{4}$	$-3.676 \cdot 10^{13}$
REC East	$1.630 \cdot 10^{-2}$	$5.192 \cdot 10^{4}$	$-6.423 \cdot 10^{13}$
Q1 West	$4.026 \cdot 10^{-3}$	$1.170 \cdot 10^{4}$	$-1.505 \cdot 10^{12}$
Q1 East	$1.270 \cdot 10^{-2}$	$1.170 \cdot 10^{4}$	$-1.505 \cdot 10^{12}$
Q2 West	$1.469 \cdot 10^{-2}$	$6.042 \cdot 10^{3}$	$-1.131 \cdot 10^{12}$
Q2 East	$5.106 \cdot 10^{-3}$	$8.397 \cdot 10^{3}$	$-1.222 \cdot 10^{12}$
Mark II	0.0	$1.094 \cdot 10^{5}$	$-7.541 \cdot 10^{13}$

  Here $K1L$ is the quad strength and all multipoles are normal type.

- Sextupoles. To calculate nonlinearity generated by sextupoles the following equations have been used.

$$K8L\,[1/m^8] \;=\; 7.2 \cdot 10^{10} \cdot K2L\,[1/m^2]$$

  Here $K2L$ is the sextupoles strength and the corresponding multipoles are normal type.

- Horizontal separators. The following expressions have been used to calculate its effective nonlinearity.

$$\begin{aligned} K2L\,[1/m^2] &= 5.674 \cdot 10^{1} \cdot \theta\,[rad] \\ K4L\,[1/m^4] &= -1.703 \cdot 10^{6} \cdot \theta\,[rad] \end{aligned}$$

  Here θ is the deflection angle, corresponding multipoles are normal type.

- Vertical steerings in sextupole magnets. The effective nonlinearity of these elements was calculated as:

  $$K4L\,[1/m^4] \;=\; -1.824 \cdot 10^6 \cdot \theta\,[rad]$$

  Here θ is the deflection angle. Corresponding multipoles are skew type.

It must be mentioned that *the completed information about nonlinear components of the all CESR elements is in not available.* In the presenting simulation only the precise known nonlinearities of magnetic elements have been used. In addition, there is another kind of magnetic field nonlinearity described in [3]. It is the field perturbation due to the magnetic material contained in CESR IR beam pipe. The strength of it was estimated but not exactly known. Thus it has not been included in model. This type of field distortion as well as the other unknown parasitic magnetic fields may cause the difference between measurements and calculations.

Tunes Variation

The most obvious evidence of the CESR leading magnetic field nonlinearity is the betatron tunes variation with orbit displacement. Figure 1 shows the measured and calculated dependence of betatron tunes versus so called $PR1$ orbit distortion. This type of distortion made with electrostatic plates is been using at CESR to separate counter rotating beams in horizontal plane at the parasitic interaction points. Horizontal axes on plot gives the distortion amplitude in relative units, 1000 of it corresponds to approximately $6mm$ of horizontal orbit offset in arcs. Vertical axes is the tunes shift.

One can see negligible difference between measurement and calculation for horizontal tune shift and the bigger difference for vertical tune shift. One of the reason for this difference may be the ignored magnetic field distortions in REC quads caused by known imperfection of vacuum chamber, see [3]. As at these quads location the vertical beta-function is much bigger than horizontal one, the effect of the field perturbation on beam dynamic in vertical plane is much bigger than in horizontal.

The next plots 2 and 3 show the calculated effect of the two main contributors into the betatron tunes variation. These are Mark II quads used in regular structure in arcs and the horizontal separators.

The total horizontal tune shift is about 8kHz at 3000 units of $PR1$ and depends on pretzel as $PR1^4$. The quads nonlinearity gives approximatly 5kHz of tune rise, it is 60 % of the total amount. Horizontal separators give additional 3 kHz or 40 %. The effect of these nonlinearities on vertical tune is 2.7 times smaller, see figure 3.

Resonance Excitation and Coupling Difference

Another effect caused by nonlinear components of leading magnetic field is the resonances excitation and the coupling difference between two beams due to its orbit difference. Resonance excitation results in the vertical beam emittance growth as well as in the beam lifetime reduction. The coupling difference may cause the vertical size variance between two beams and its misaligment in IP. All that may hurt the machine performance. The tune scanning technique developed in [4] has been used to observe the resonances at CESR. Figure 4 and 5 show the result of two tune plane scans made with flatten orbit and with orbit distorted with pretzel. The both figures show vertical beam size. In the case of flatten orbit, figure 4, one can see $f_h - f_v + f_s = nf_0$ resonance line crossed tune plane from lower left corner to the right upper. Is is manifested by the vertical beam size increase. At the right lower corner there is trace of $f_h - f_v = nf_0$ resonance. In the case of pretzeled orbit, figure 5, the resonance $f_h - f_v + f_s = nf_0$ became stronger and the additional resonance $3f_h - f_v = nf_0$ is appeared.

The simulation of these two tune plan scans was done with tracking using MAD program. The quads nonlinearities have been calculated from designed quads strength. The sextupoles nonlinear field components were determined using CESR save set and the coefficients described above. The same save set was used to determine the vertical steering deflecting angels and the steering nonlinearities. In model structure the steering angels was omitted and only its nonlinearities were included. The particles starting points for tracking were chosen nearby the beam center: $1.5\sigma_v$ in vertical, $1.5\sigma_h$ in horizontal plane and $1.5\sigma_e$ for synchrotron motion. It is in so called the beam core region, where the particles motion distortion must be seen as beam size change. The 40x40 grid in tune plane has been used to scan. In each of the 1600 points, 800 turns was tracked and the maximums of vertical and horizontal amplitudes have been recorded. Figure 6 and 7 show the results of tracking. The first one been for the case of flatten orbit does not indicate any resonances in range $f_h > 205kHz$ where is the CESR working point is usually placed and where is experimental tune scan was done. In contrary with it the tracking with pretzeled orbit, see figure 7, shown the $f_h - f_v + f_s = nf_0$ and $3f_h - 3f_v = nf_0$ resonances appearance. It is consist with experimental facts. The next step was to identify the elements caused these resonances excitation. Figure 8 is result of tracking under the same condition as previous but without vertical steering nonlinearity. Here is no $f_h - f_v + f_s = nf_0$ and $3f_h - f_v = nf_0$ resonances. So, one can conclude that vertical steering nonlinearity is responsible for these resonances excitation.

Note that in the real machine experiments, it is not easy make such identification. Any change of vertical steering nonlinearity is been accompanied with the change of its deflection angle leading to the beam orbit displacement. Due to that there are many other parasitic effects masking wanted ones.

Let's rate CESR vertical steerings according to its resonance driving strength. It may be done in the following way. Consider ring with only one vertical steering. The Hamiltonian, H, describing particals motion may be written as:

$$H = H_0 + S(z) \cdot y \cdot x^4 \tag{1}$$

Here the second term on the right side is for vertical steering nonlinearity effect. It describes vertical kick, which depends on horizontal coordinate as x^4. Function $S(z)$ gives the strength of steering and its locations. The term H_0 on the right side of 1 is for the rest of the elements. The horizontal coordinate x may be written as:

$$x = x_\beta + x_s + p \tag{2}$$

Here x_β describes betatron motion, x_s is for synchrotron, p is orbit offset due to pretzel. Make standard transformation to action-angle variables and substitute equation 2 into 1 one can obtain:

$$H = H_0 + S(\theta) \cdot \epsilon_y^{1/2} \beta_y^{1/2} \cdot cos(\phi_y) \cdot (\epsilon_x^{1/2} \beta_x^{1/2} \cdot cos(\phi_x) + \epsilon_e \eta cos(\phi_s) + p)^4 \tag{3}$$

Here β_x, β_y and η are horizontal, vertical betatron functions and dispersion in the steering location; ϵ_x, ϵ_y and ϵ_e are action variables corresponding to the horizontal, vertical and synchrotron motion; ϕ_x, ϕ_y, ϕ_s are phase variables. After simple algebraic manipulation one can determine terms responsible for the discussed above resonances driving and for the effect of the coupling difference between two beams.

- The coupling difference driving term.

$$V_{coupl} \sim \beta_x^{1/2} \beta_y^{1/2} p^3 \tag{4}$$

- The $f_h - f_v + f_s = nf_0$ resonance driving term.

$$V_{f_h - f_v + f_s = nf_0} \sim \beta_x^{1/2} \beta_y^{1/2} \eta\, p^2 \tag{5}$$

- The $3f_h - f_v = nf_0$ resonance driving term.

$$V_{3f_h - f_v = nf_0} \sim \beta_x^{3/2} \beta_y^{1/2} p \tag{6}$$

So, in order to rate the vertical steerings according to its resonance driving strength, the combination of β functions, dispersion and pretzel on the right side of equations 4,5 and 6 must be used as criteria.

The table below shows this rating.

Coupling difference		$3f_h - f_v = nf_0$ driving		$f_h - f_v + f_s = nf_0$ driving	
V. str	rel. strength	V. str	rel. strength	V. str	rel. strength
V34	2.381e+05	V34	16564	V34	1.93252e+04
V10	1.313e+05	V10	8853.0	V10	9.61728e+03
V33	6.309e+04	V08	6445.9	V08	8.63999e+03
V08	5.585e+04	V33	5380.8	V33	5.40950e+03
V09	4.030e+04	V09	2550.6	V09	3.99708e+03
V17	3.240e+04	V17	2347.9	V17	3.94023e+03
V43	2.629e+04	V43	1836.2	V43	3.00401e+03
V39	2.247e+04	V19	1661.9	V29	2.36570e+03
V35	2.053e+04	V39	1458.9	V19	2.17108e+03
V19	2.046e+04	V13	1366.5	V35	2.09400e+03
V13	2.028e+04	V35	1279.0	V39	1.87708e+03
V29	1.653e+04	V29	1047.2	V23	1.46777e+03
V23	8.807e+03	V27	934.67	V25	1.04609e+03
V25	4.363e+03	V25	875.35	V27	9.36444e+02
V27	3.758e+03	V23	620.02	V13	4.55201e+02
V45	2.308e+03	V37	479.43	V37	3.33242e+02
V37	1.313e+03	V11	238.82	V45	3.20943e+02
V11	5.185e+02	V21	156.71	V21	2.36794e+01
V21	2.241e+01	V45	149.06	V15	1.96517e+01
V15	1.413e+01	V15	52.460	V11	1.39940e+01
V31	5.269e-01	V31	36.740	V31	1.83767e+00
V41	3.150e-01	V41	23.296	V41	1.18577e+00

One can see that the same set of vertical steerings given the main contribution into all three effects. All they are located in the positions with big pretzel amplitude. The use of it must be avoided.

Conclusion

The known nonlinear field components of CESR elements have been included into the model structure.

Using program MAD the dependence of betatron tunes versus beam orbit displacement around ring was calculated. It is in good agreement with measurements. It was found that the main sours of this tune shift is the nonlinearity of Mark II quads used in regular structure of CESR arcs and the horizontal separators electric field nonuniformaty at big horizontal offset.

The analysis of tune scan data and its comparison with tracking simulation made with MAD allowed to identify elements resposable for nonlinear coupling resonance excitation near CESR working point at pretzeled orbit. These are vertical steerings located at positions with big pretzel amplitude.

Realizing these facts one can plan effective measures to improve CESR perfomance.

Acknowledgments

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References

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[2] The MAD Program, Version 8.1, CERN/SL/90-13 (AP)

[3] A. Temnykh and D. Rubin, Effect of Q1-Q2 and REC Vacuum Chamber Welds on Dynamic Aperture, CBN 96-1, Cornell 1996

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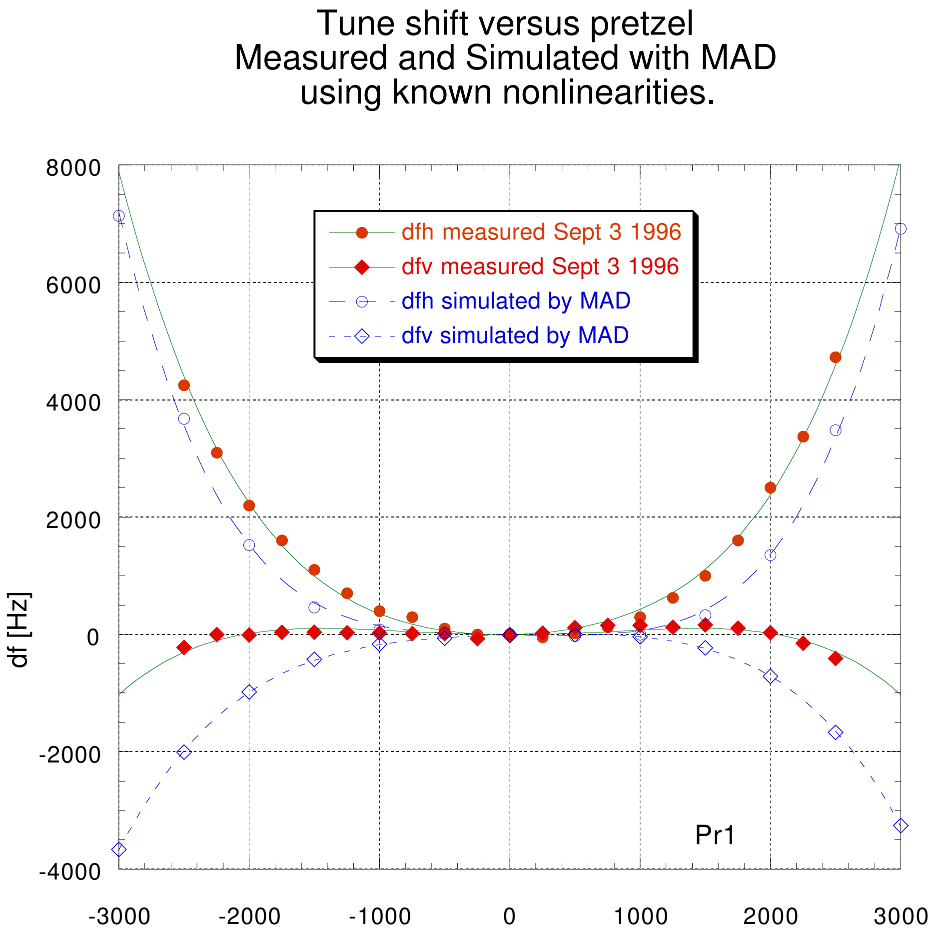

Figure 1: Measured and calculated betatron tune shift versus $PR1$ orbit distortion

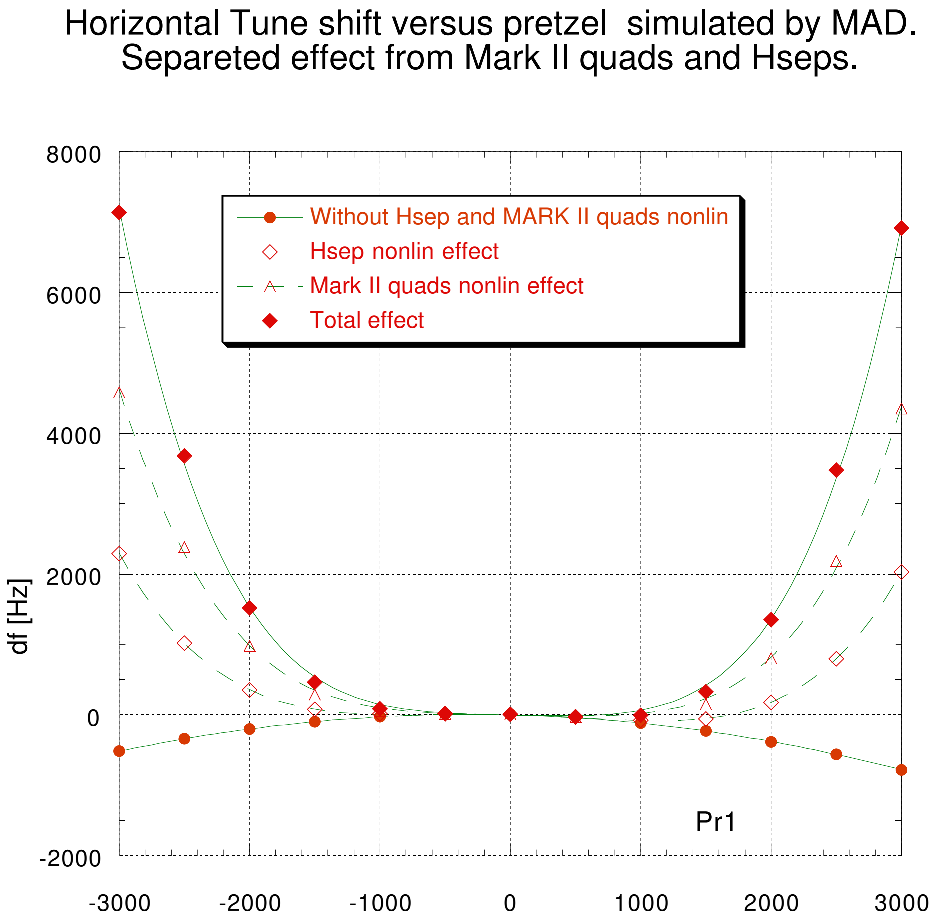

Figure 2: The contribution of the Mark II quads nonlinearity and horizontal separators field nonlinearity into horizontal tune shift.

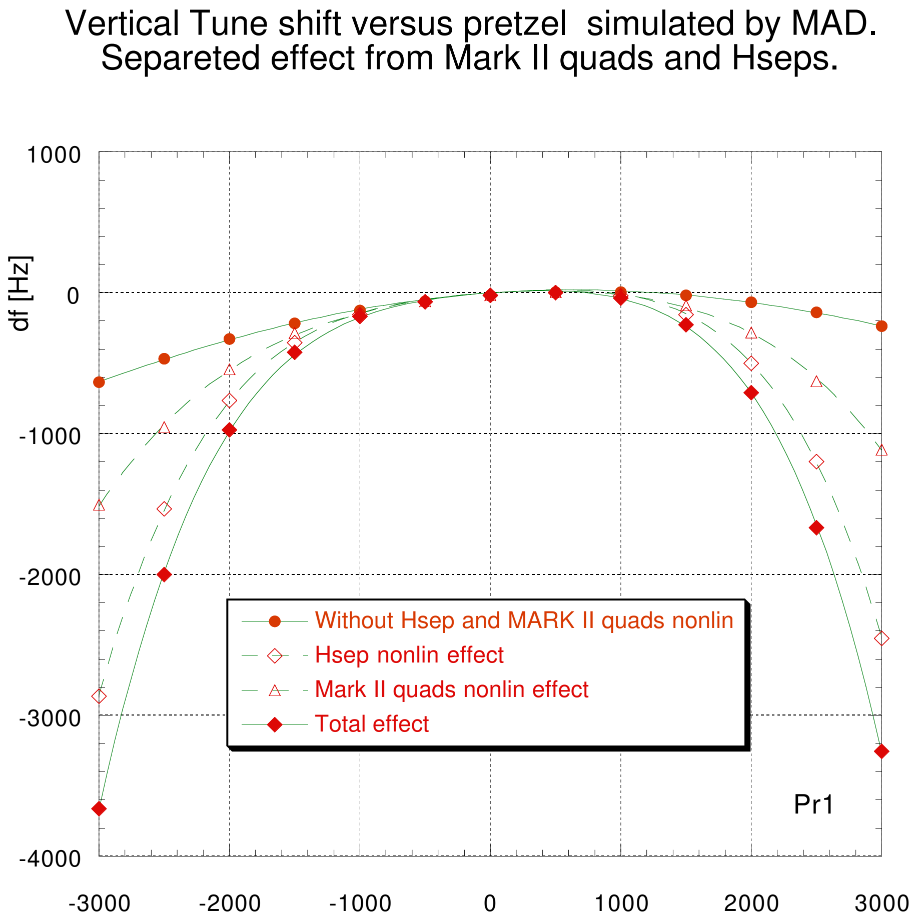

Figure 3: The contribution of the Mark II quads nonlinearity and horizontal separators field nonlinearity into vertical tune shift.

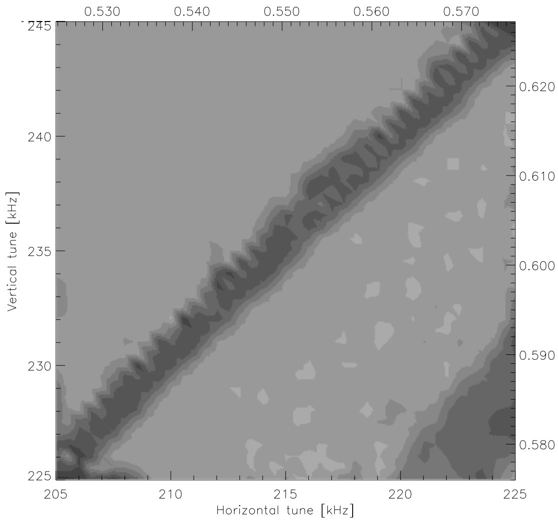

Figure 4: Real tune plane scan at CESR with flatten orbit. Vertical beam size is shown. Line crossing the tune plane from the left bottom to right up is $f_h - f_v + f_s = nf_0$ resonance.

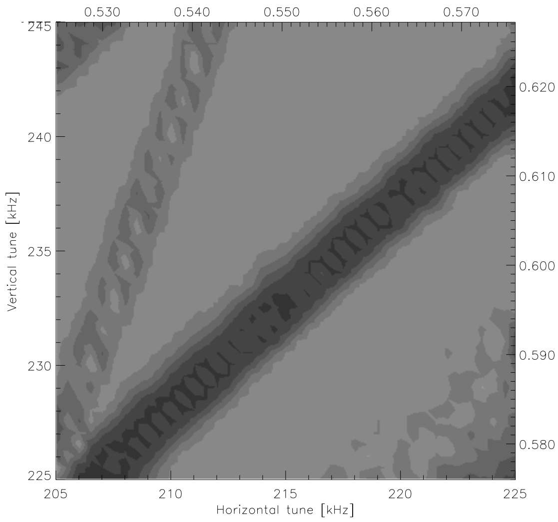

Figure 5: Real tune plane scan at CESR with pretzeled orbit. Vertical beam size is shown. In addition to $f_h - f_v + f_s = nf_0$ resonance one can see the appearance of $3f_h - fv = nf_0$ resonance.

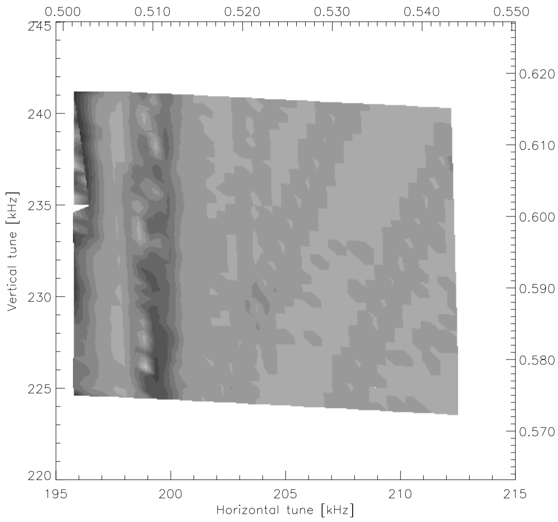

Figure 6: The simulation of tune plane scan with flatten orbit. Maximum of vertical amplitude during 800 turns is shown. Starting points for tracking are in the beam core.

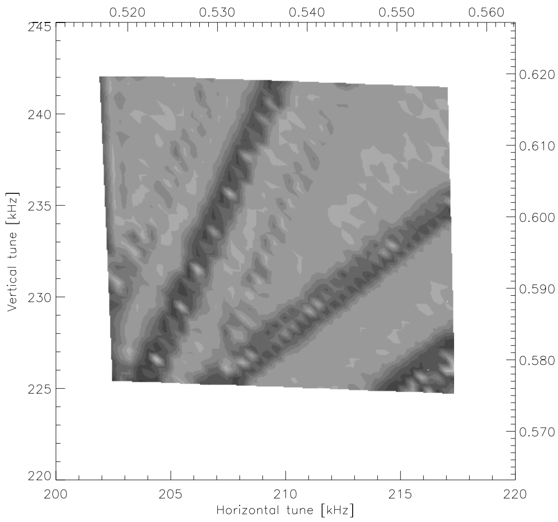

Figure 7: The simulation of tune plane scan with pretzeled orbit. Maximum of vertical amplitude during 800 turns is shown. Starting points for tracking are in the beam core.

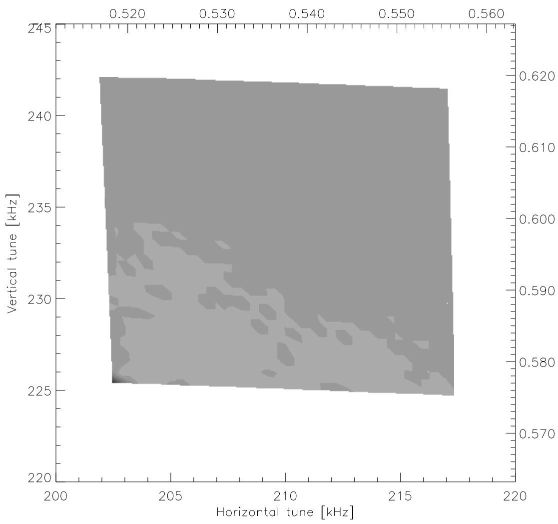

Figure 8: The simulation of tune plane scan with pretzeled orbit without vertical steering nonlinearity. Maximum of vertical amplitude during 800 turns is shown. Starting points for tracking are in the beam core.