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Betatron Tune Correction Simulations in the ALBA Storage Ring

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Abstract

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We report the study of three different betatron tune correction methods at the ALBA storage ring through simulations in the Matlab Accelerator Toolbox (AT). The methods use either two, eleven or fourteen independent qudrupole families to correct the betatron tune. In the latter case, a minimization constraint in the beam's beta beating is implemented. Further, insertion devices (IDs) are simulated to study realistic sources of errors in the storage ring.

I. INTRODUCTION

In particle accelerators the working point influences strongly the performance of the machine. This point is specified by setting both components of the betatron tune number, Q_x and Q_y. In order to have a good performance of the accelerator the working point should remain constant while the machine is operating. Therefore, it is important to set the tune to the value in which the working point is achieved and keep it unchanged.

However, real accelerators have several sources of errors that tend to displace the machine from its working point. We can distinguish between two main types of error sources: the ones that modify the nominal behaviour of the machine slowly, as the rising of the temperature in the quadrupoles or other components of the ring; and the ones that introduce perceptible errors in a short period of time, as the insertion devices when its gap is open or closed. It is then clear that this errors must be corrected systematically if a good performance of the machine is desired. A common way to correct these errors is using the quadrupoles spread along the storage ring. By changing its strength one can modify the beam parameters to reset the working point. Quadrupoles of the same type −same quadrupole strenght and lenght− form families of quadrupoles. At ALBA each family contains eight quadrupoles and there are fourteen families, ten with horizontal focusing (QH) and four with vertical focusing (QV). A certain configuration of these quadrupole families allows building the machine's lattice with a certain symmetry.

In this work we present a series of simulations that implement various correction schemes in the ALBA storage ring. At the moment, only six IDs are located at ALBA but in the future it is expected to host more experiments, which means more IDs for the beamlines and a consequent increase of the modification of the beam. Therefore, a feedback system will be needed to correct systematically this errors and ensure the stability of the accelerator. The goal of this simulations is to study these correction methods to later implement them as online feedback system at the ALBA synchrotron.

II. BEST PAIR OF QUADRUPOLE FAMILIES

The first thing we did is to study which are the pair of quadrupole families that best correct the tune variations from the nominal values. We started making the assumption that the pair of quadrupole families that best correct the tune are such that the area covered by the vectors in the shifted-tune space is maximum. Here, shifthed-tune space is the set of points $(\Delta Q_x, \Delta Q_y)$ and the vectors are the quantities that expand from the origin to a certain point in the space.

To produce these tune shifts we have slightly varied the quadrupole strength, k, of the quadrupoles in the simulated ring of the AT. This has been done by changing each time the quadrupole strength of just one quadrupole family in order to have a total change of $\Delta k = 0.01$ m^{-2}. This means that each quadrupole of the family has been varied a quantity $\Delta k = 0.01/8$ m^{-2}, since there are eight quadrupoles per family. To add this Δk, we have changed both the second component of PolynomB and the quadrupole strength itself, k, in the AT code.

To preserve the symmetry of the lattice in each quadrant and, particularly, in the unit cell, we have taken into account that families QV03-QV04, QH07-QH10 and QH08-QH09 have to be changed simultaneouly and therefore the quadrupole strength change is $\Delta k = 0.01/16$ m^{-2}.

The result of this simulation is shown on the top of Fig. 1. The plot present ΔQ_x and ΔQ_y produced by the modification of the quadrupole strength of each quadrupole family. In order to find out the best family pair using our assuption we have computed the area covered by each pair of shifted-tune vectors. The result is shown on the bottom of Fig. 1, showing up, according to this assumption, that the quadrupole families that best correct the tune variations are the QH03 family and the QH07-QH10 families.

III. TUNE SHIFT CORRECTION

The next step was to use the previous calculation to correct the tune shifts produced by random errors in the quadrupoles. To do so, we have considered that the effect of a quadrupole familiy is independent of each other and

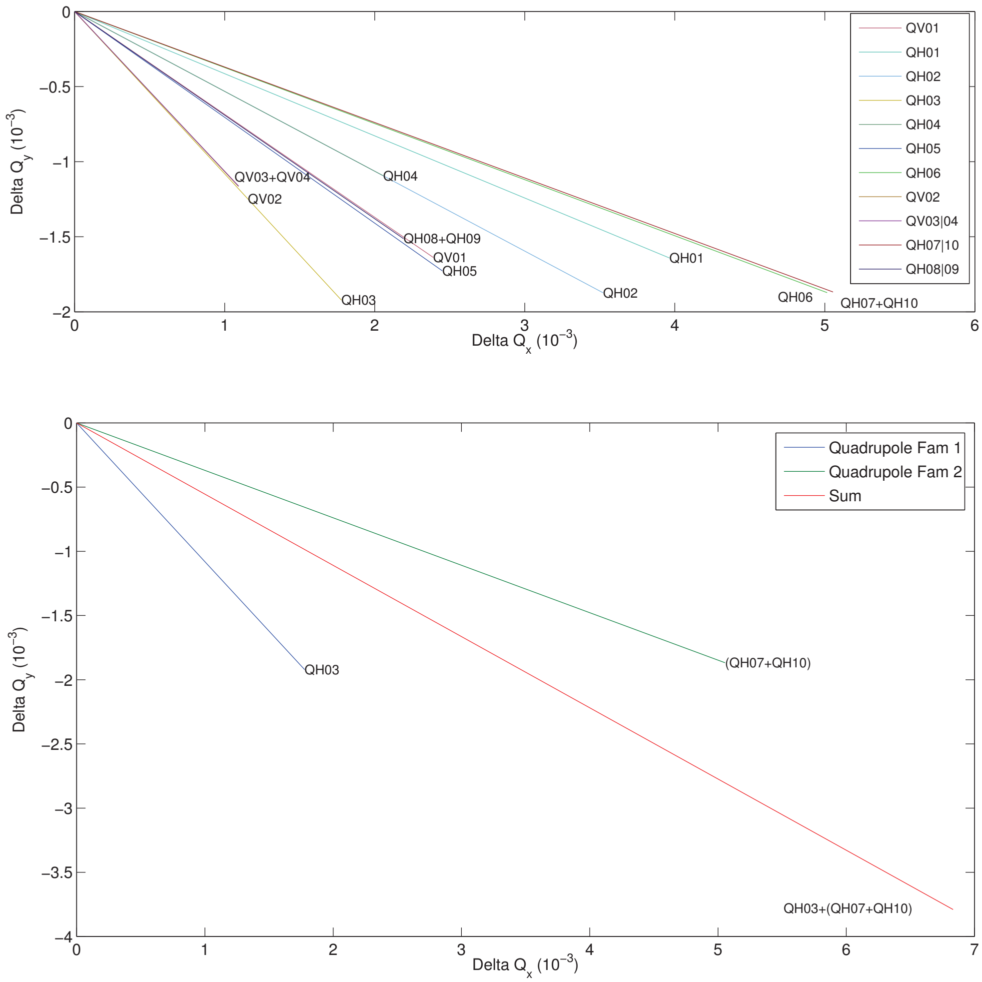

FIGURE 1: (Above) Shifted-tune space of the shifted-tune vectors produced by the excitation of each quadrupole family independently. (Below) Shifted-tune with the two shifted-tune vectors that cover the maximum area.

that the tune shift is linear with the quadrupole strength needed to correct the tune, that is

$$\Delta \mathbf{Q} = \mathbf{M} \Delta \mathbf{k}, \tag{1}$$

where Δk is the quadrupole excitation that we introduce, ΔQ is the tune variation induced by the quadrupole excitation and M is the response matrix to be determined. Assuming that the quadrupole families are independent of each other we can write

$$\Delta \mathbf{Q}^{(1)} = \mathbf{M} \begin{pmatrix} \Delta k \\ 0 \end{pmatrix}, \tag{2}$$

$$\Delta \mathbf{Q}^{(2)} = \mathbf{M} \begin{pmatrix} 0 \\ \Delta k \end{pmatrix}, \tag{3}$$

where the superindices refer to the quadrupole families. In our particular case these are QH03 and QH07+QH10 families. The solution to these equations is

$$\mathbf{M} = \frac{1}{\Delta k} \begin{pmatrix} \Delta Q_x^{(1)} & \Delta Q_x^{(2)} \\ \Delta Q_y^{(1)} & \Delta Q_y^{(2)} \end{pmatrix} \simeq \begin{pmatrix} 0.1778 & 0.5055 \\ -0.1922 & -0.1868 \end{pmatrix}. \tag{4}$$

With this response matrix, $\mathbf{M}$, now we can compute which is the $\Delta \mathbf{k}_{\text{cor}}$ we shall apply to the quadrupoles in order to correct the variation of the tune from the nominal values. Hence, the correction problem is left to the equation

$$\Delta \mathbf{k}_{\text{cor}} = -\mathbf{M}^{-1} \Delta \mathbf{Q}_{\text{meas}}. \tag{5}$$

To study this correction, denoted by 2Q, we have performed a series of simulations introducing random errors normal distributed –with $\sigma = 3 \times 10^{-3}$ m^{-2}– in the quadrupoles. The results of these simulations are shown in Fig. 2: the histograms on the top show the plot of the

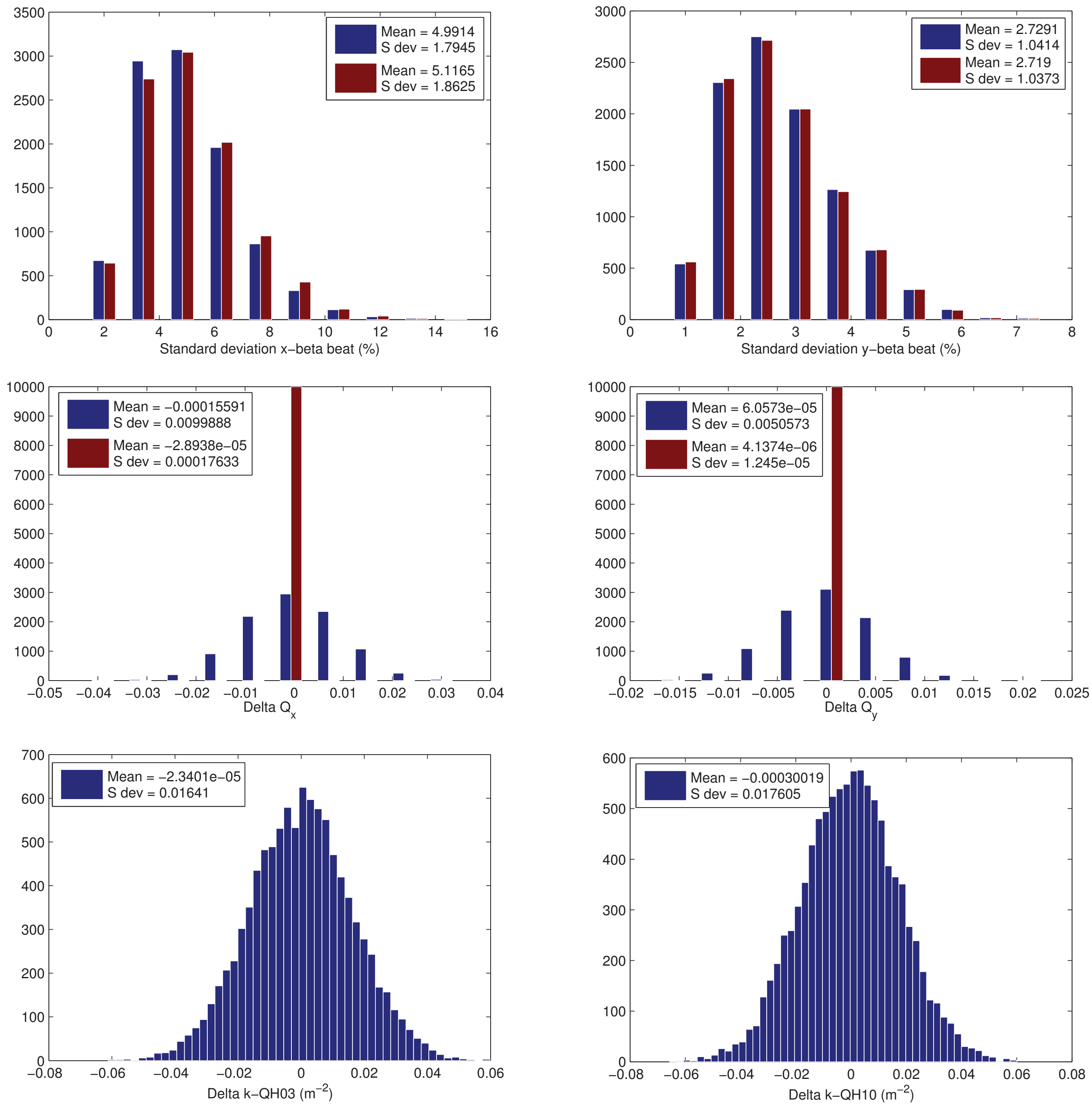

FIGURE 2: The graphs show the histograms of the standard deviation of the beta beating (%), the tune variation and the quadrupole strength needed to correct the tune for each component. In the first four histograms, the blue colour refers to ring with the errors and the red colour to the corrected ring.

beta beat's standard deviation measured at the BPMs for both components and for each ring –with errors (blue) and corrected (red); the histograms in the center refer to the tune shift produced by both the ring with errors and the corrected ring. It is remarkable that all tune variations of the corrected ring lie on the same central bin. This means that our correction works rather good and that indeed it corrects the tune change induced by the errors in the quadrupoles; in the bottom there are the histograms of the qudrupole strength needed to correct

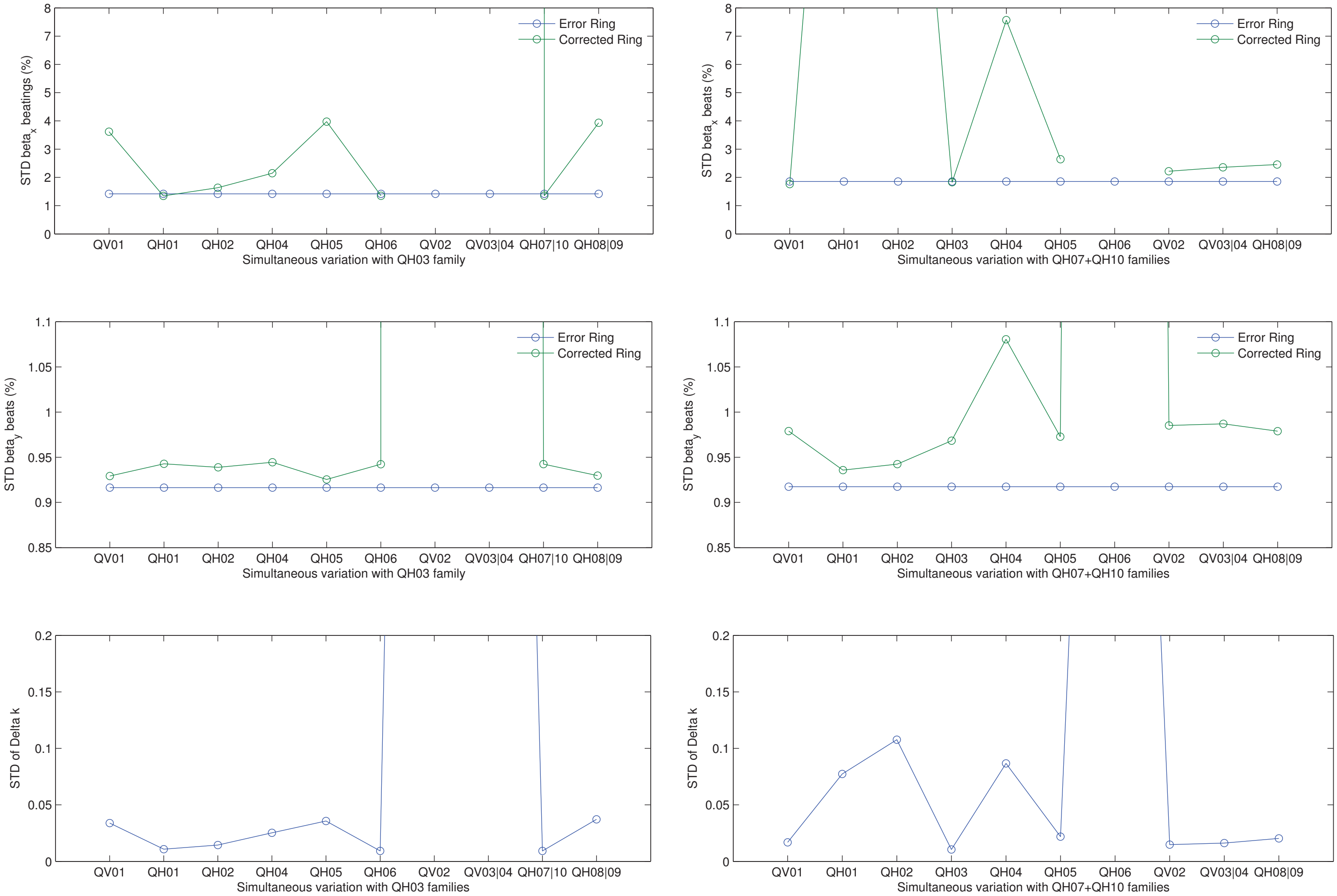

FIGURE 3: The plots show the standard deviation of the beta beat and the correction quadrupole strength for 20 simulations combining in pairs the different quadrupole families. In the left-hand side the plots correspond to the combination of the QH03 family with the rest and the right-hand side the QH07+QH10 with the rest of families.

the tune, which have been computed using Eq. (5).

IV. COMPARISON WITH OTHER QUADRUPOLES

In order to check the validity of our hypothesis we have performed the same previous simulations combining the QH03 and QH07+QH10 families, independently, with each of the rest qudrupole families. The results of these simulations are shown in different plots in Fig. 3. The left-hand side shows the standard deviations of the beta beating for both planes and the standard deviation of the correction quadrupole strenght when the QH03 family is combined with each of the other families. On the right-hand side the same plots are shown but for simulation combining QH07+QH10 families with the others.

It is possible to see how the smallest beta beat corresponds to the combination of the quadrupole families that we have chosen to be the ones that best correct the tune, *i.e.* QH03 and QH07+QH10. It is worth to notice that the QH06 family also produces a small beta beat. This can be easily explained going back to Fig. 1, where the shifted-tune vector of the QH06 family is quite close to the QH07+QH10, so that the area covered by QH06 and QH03 is just a bit smaller than the one formed by QH03 and QH07+QH10. Besides, the bottom plot shows the quadrupole strenght, Δk, we should apply in order to correct the tunes. Here we can also see that the smallest Δk appears whenever the QH03 family is combined with the QH07+QH10 families. But also the QH06 family requires a small Δk to correct the tune, suggesting that this family also could be a good choice for the correction.

The same results are extracted from the analysis of the

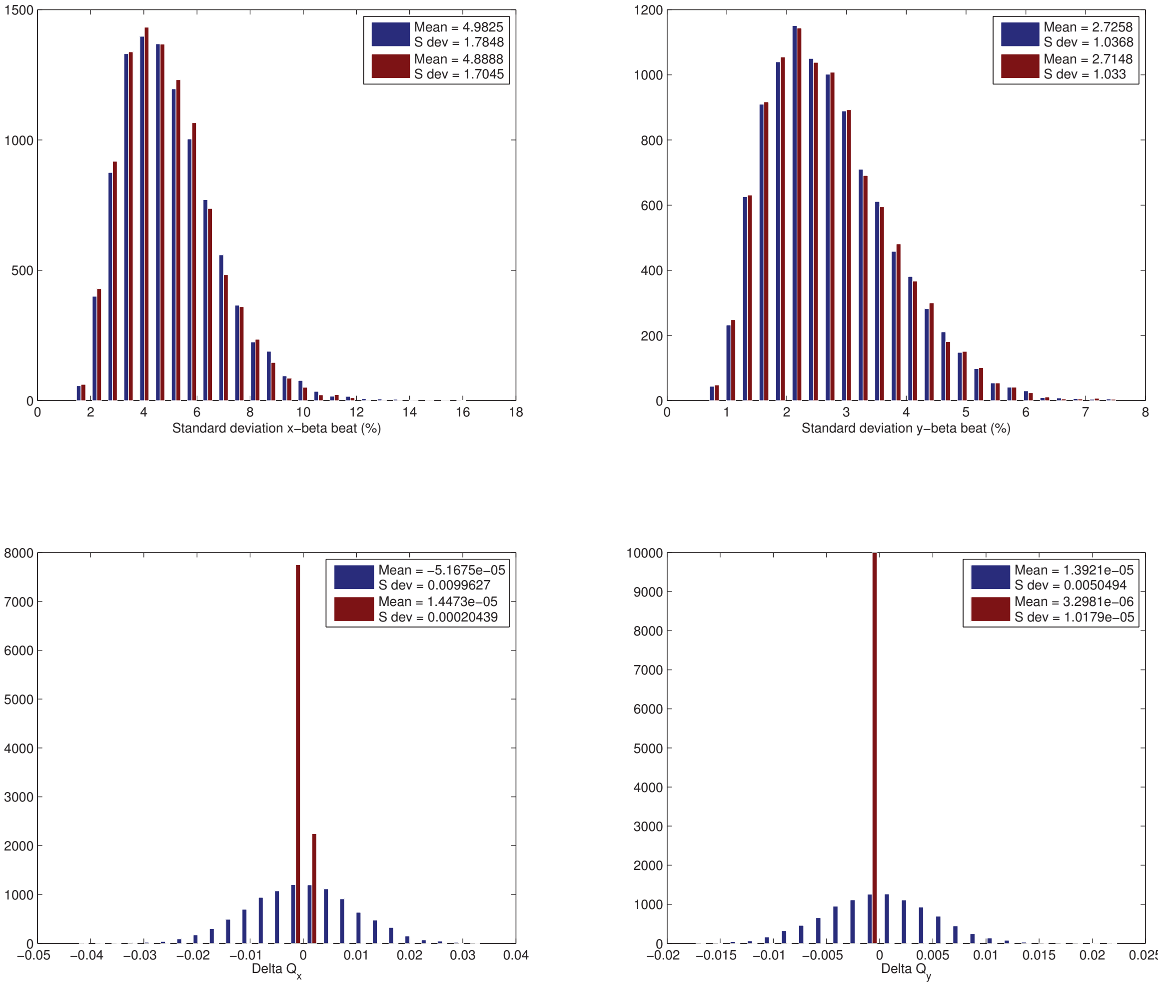

FIGURE 4: Distribution of the beta beat's standard deviation and tune shift for simulations using all quadrupole families as correctors respecting the lattice unit cell symmetry.

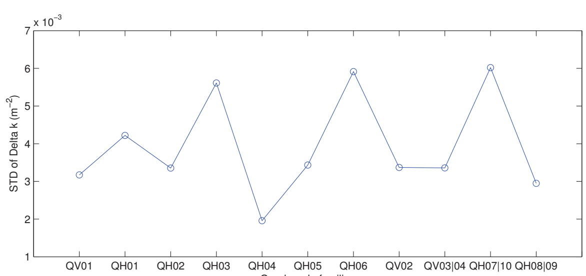

FIGURE 5: Standard deviation of the quadrupole strength correction needed to correct the tune with all the families respecting the lattice unit cell symmetry.

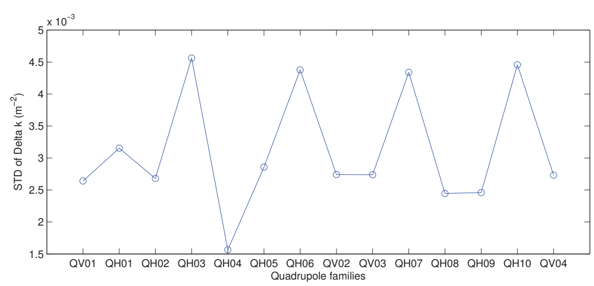

FIGURE 6: Standard deviation of the quadrupole strength correction needed to correct the tune with all the families without respecting the lattice unit cell symmetry.

simulations combining this time the QH07+QH10 families with the others. Here we see that the smaller beta beat and correction Δk are produced by the combination of our selected best families. Further, the combination of QH07+QH10 and QH05 or QV01 also produce relatively good corrections. As in the previous case we can see in

Fig. 1 the the shifted-tune vectors of these families generate the largest areas.

In this same fashion we can see that the opposite happens whenever shifthed-tune vectors of relatively same angle and size, *i.e.* they form rather small areas, are combined. In these situation we see divergences in the beta beats and in the correction quadrupole strength, for example in the combination of the QH03 and QH05 or QV01, as well as combining QH07+QH10 with QH06 or QH02.

V. ALL QUADRUPOLES CORRECTION

Two quadrupole families are enough to correct the tune. However, correction with all quadrupole families could be more interesting in certain cases. The process to obtain the correction is similar to the previous one, the only difference is that now the response matrix is computed for the response of each quadrupole family, and it adopts the form

$$\mathbf{M} = \frac{1}{\Delta k}\begin{pmatrix} \Delta Q_x^{(1)} & \cdots & \Delta Q_x^{(11)} \\ \Delta Q_y^{(1)} & \cdots & \Delta Q_y^{(11)} \end{pmatrix}. \tag{6}$$

The matrix has dimension 2×11 because we are still preserving the symmetry of the lattice unit cell, where the families QV03-QV04, QH07-QH10 and QH08-QH09 are to be changed simultaneously. We will denote this method by 11Q.

This case is a bit different from the previous one. Equation (6) leads to a overdetermined system of linear equations since we have two constraints and eleven free parameters. Actually, $\mathbf{M}$ is no longer a square matrix and usual matrix inversion methods cannot be applied. To invert, or pseudo-invert, the matrix we used the *singular value decomposition* method (SVD), commonly used for this purpose. The method states that a $m \times n$ matrix $\mathbf{M}$ can be decomposed as

$$\mathbf{M} = \mathbf{U}\mathbf{S}\mathbf{V}^{\intercal}, \tag{7}$$

where $\mathbf{U}$ is $m \times m$ unitary matrix, $\mathbf{S}$ a $m \times n$ non-degenarate diagonal matrix and $\mathbf{V}$ a $n{\times}n$ unitary matrix. It can be proved that the pseudo-inverse of $\mathbf{M}$ is

$$\mathbf{M}^{-1} = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^{\intercal}, \tag{8}$$

where $\mathbf{S}^{-1}$ is the pseudo-inverse of $\mathbf{S}$, *i.e.* $\mathbf{S}_{ii}^{-1} = 1/\mathbf{S}_{ii}$.

The results of the simulations with this method are shown in Fig. 4, where the standard deviation of the beta beating and the tune shift after the correction are plotted. Comparing the first row of Fig. 2 and Fig. 4 we see that the beta beating produced in the correction is quite similar in both methods as well as the tune correction shown in the second row. Figure 5 shows the standard deviation of the correction quadrupole strength. As expected, the correction is distributed along all the quadrupole families showing peaks of maximum values for the QH01, QH03, QH06 and QH07-QH10 families. The fact of having peaks of quadrupole strength for these families is not surprising. If we return to examine Fig. 1, we can see that although the quadrupole families that form the biggest area in the shifted-tune space are the QH03 and the QH07-QH10, there are other quadrupole families that are also good candidates to fulfil this requirement, for example QH01 and QH06.

Next subsection studies the effects of this correction when the insertion devices are added to the lattice.

A. Errors produced by insertion devices

Insertion devices (IDs) introduce variations in the nominal beam parameters such shifts in the tune as well as in other optical properties of the beam, as the beta functions. In this part we have performed the simulations introducing IDs in the ring lattice using kickmaps. Then we calculated the tune shift independently produced by each ID and the beta beating at each BPM. Finally, we used our correction model to try to restore the ring parameters to its nominal values.

We found that such scheme corrects the tunes within 10^{-4} in the worst cases, *e.g.* EPU125$_{\mathrm{V}}$ and SCW31, and 10^{-6} for the best ones, *e.g.* IVU21 and EPU62/71. The results of the simulations are shown in Table I. There we can see that the introduction of IDs produces, in most cases, a beta beat even when the tunes are corrected. Moreover, when we apply the correction the beta beat increases substantially.

VI. CORRECTION WITH BETA BEATING MINIMIZATION

Although the previous tune correction methods have been proved to work correctly, there are other parameters that are not taken into account in the process, as for example the optics of the beam. We have already remarked that the beta beating of the beam increases largely when introducing the IDs (Table I), and even further, the correction applied by the previous methods worsen it considerably. It is, therefore, interesting to implement a correction method such that it does not worsen the beta beating.

From Eq. (5) it is clear that $\mathbf{M}$ is a linear application that maps the correction vector space, K, to the tune space, Q, that is

$$\begin{aligned} \mathbf{M}:\ & \mathsf{K} \to \mathsf{Q} \\ & \Delta\mathbf{k} \mapsto \Delta\mathbf{Q} = \mathbf{M}\Delta\mathbf{k}. \end{aligned}$$

By assuming $\mathbf{M}$ to be a linear map we know that there exist a set of $\Delta\mathbf{k}_{\mathrm{ker}} \in \mathsf{K}$ such that $\mathbf{M}\Delta\mathbf{k}_{\mathrm{ker}} = \mathbf{0}$. This set $\{\Delta\mathbf{k}_{\mathrm{ker}}\}$ is called the kernel or null space of $\mathbf{M}$, ker($\mathbf{M}$). The important thing of this is that there exist a set of correction quadrupole strengths $\{\Delta\mathbf{k}_{\mathrm{ker}}\}$ that when added

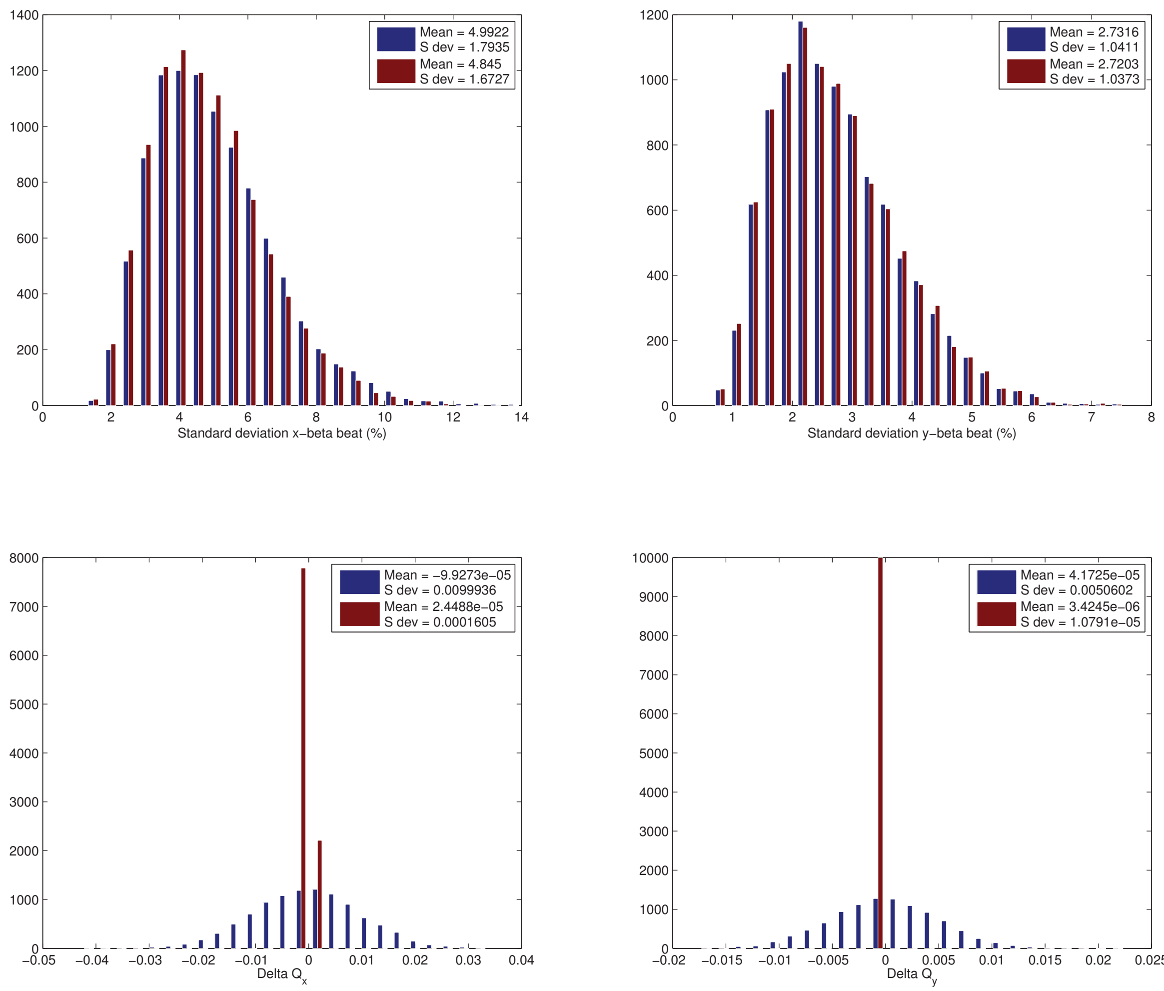

FIGURE 7: Distribution of the beta beat's standard deviation and tune shift for simulations using all quadrupole families as correctors.

to our correction $\Delta\mathbf{k}_{\rm cor}$ the tune remains invariant, *i.e.*

$$\mathbf{M}(\Delta\mathbf{k}_{\rm cor}+\Delta\mathbf{k}_{\rm ker})=\mathbf{M}\Delta\mathbf{k}_{\rm cor}+\mathbf{M}\Delta\mathbf{k}_{\rm ker}=\mathbf{M}\Delta\mathbf{k}_{\rm cor}. \tag{9}$$

This allows us to move on a perpendicular plane in the tune space where the tune remains invariant but the beta beating changes. The goal of this method is to move in this plane until arrive to a $\Delta\mathbf{k}_{\rm ker}$ where the beta beating is minimum.

To compute $\Delta\mathbf{k}_{\rm ker}$ we followed the prescription of the response matrix. In this case, unlike the previous one, we measure the beta beating produced by a $\Delta k = 0.01\ {\rm m}^{-1}$ in the quadrupoles and not the tune shift. Therefore, the response matrix is

$$\mathbf{M}_\beta=\frac{1}{\Delta k}\left(\frac{\Delta\boldsymbol{\beta}^{(1)}}{\boldsymbol{\beta}}\cdots\frac{\Delta\boldsymbol{\beta}^{(12)}}{\boldsymbol{\beta}}\right), \tag{10}$$

where $\boldsymbol{\beta}$ is a vector containing the horizontal component of the beta function and consecutively the vertical component. Further, $\dim(\mathbf{M}_\beta)=240\times 12$ where 240 is two times the number of BPMs and 12 is the column dimension of the kernel of $\mathbf{M}$, *i.e.* $\dim[\ker(\mathbf{M})]=14\times 12$. Finally, the quadrupole strength in the kernel of $\mathbf{M}$ is computed as

$$\Delta\mathbf{k}_{\rm ker}=-\ker(\mathbf{M})\,\mathbf{M}_\beta^{-1}\,\Delta\boldsymbol{\beta}/\boldsymbol{\beta}_{\rm meas}, \tag{11}$$

where

$$\Delta\boldsymbol{\beta}/\boldsymbol{\beta}_{\rm meas}=\frac{\boldsymbol{\beta}_{\rm cor}-\boldsymbol{\beta}_{\rm ID}}{\boldsymbol{\beta}_{\rm ID}}, \tag{12}$$

with $\boldsymbol{\beta}_{\rm ID}$ being the beta beating measured after the introduction of the insertion device and $\boldsymbol{\beta}_{\rm cor}$ the beta beating measured after the correction $\Delta\mathbf{k}_{\rm cor}$ is performed.

In this process we neglected the lattice symmetry, doing the correction with all the fourteen quadrupole families without taking into account that families QV03-QV04, QH07-QH10 and QH08-QH09 should be changed in the same amount to preserve the lattice unit cell symmetry.

The result of the simulations is are shown in Fig. 7 where we can see that there is no great difference if compared with the previous methods. Actually, Fig. 6 shows a similar behaviour as Fig. 5. We can see another time that the maximum values of the correction quadrupole strengths are distributed to the families QH01, QH03, QH06, QH07 and QH10 (this time QH07 and QH10 act independently).

The previous method, 11Q, produced a great increment in the beta beating when the IDs where added to the storage ring. The same simulation has been performed with this method, 14 independent quadrupole families + beta beating minimization. As has been already mentioned, this method computes a correction, $\Delta\mathbf{k}_{\mathrm{min}} = \Delta\mathbf{k}_{\mathrm{cor}} + \mathbf{k}_{\mathrm{ker}}$, that minimize the beta beating introduced by the correction itself, leaving the tune invariant. Table II shows the result of the simulations using this method. We can see that $\Delta Q^{14\mathrm{Q}}_{\mathrm{min}}$ −third column of Table II− is of the same order, and in some cases even lower, of the 11Q correction −third column of Table I.

Finally, we compare the last two columns of each Table, which present the beta beatings. First, we remember that column $\Delta\beta/\beta_{\mathrm{ID}}$ of Table I shows the beta beating produced by the introduction of IDs. Then, column $\Delta\beta/\beta^{11\mathrm{Q}}_{\mathrm{cor}}$ of Table I and column $\Delta\beta/\beta^{14\mathrm{Q}}_{\mathrm{cor}}$ of Table II show the beta beating obtained once the correction is performed without minimization. Here we can see that, in most cases, the beta beating increases in comparison with $\Delta\beta/\beta_{\mathrm{ID}}$, which is the expected behaviour when no constraint on the beta beating is imposed. On the other hand, coulmn $\beta/\beta^{14\mathrm{Q}}_{\mathrm{min}}$ shows the beta beating generated by the 14Q coreection with the constraint of minimizing the introduced beta beating. If we compare this column

ID	ΔQ_{ID} (10^{-2})	$\Delta Q^{11\mathrm{Q}}_{\mathrm{cor}}$ (10^{-5})	$\Delta\beta/\beta_{\mathrm{ID}}$ (%)	$\Delta\beta/\beta^{11\mathrm{Q}}_{\mathrm{cor}}$ (%)
SCW31	0.00/0.53	−26.72/−0.72	0.00/2.12	4.41/2.06
IVU20	0.00/0.18	−2.24/0.01	0.01/0.56	1.46/0.57
IVU21	0.00/0.08	−0.15/−0.02	0.00/0.28	0.63/0.28
IVU21	0.00/0.08	−0.15/−0.04	0.00/0.29	0.63/0.29
EPU125$_{\mathrm{H}}$	0.31/0.07	−9.17/−0.04	1.38/0.25	2.88/0.26
EPU125$_{\mathrm{C}}$	−0.60/0.63	5.69/−0.29	2.79/2.33	2.68/2.29
EPU125$_{\mathrm{V}}$	−1.48/1.15	36.75/−2.97	7.13/4.35	5.78/4.15
EPU125$_{\mathrm{apC}}$ [a]	−0.58/0.62	5.09/ − 0.26	2.69/2.30	2.64/2.26
EPU125$_{\mathrm{apV}}$	−1.48/1.15	36.75/−2.97	7.13/4.35	5.78/4.15
EPU125$_{\mathrm{Hc}}$ [b]	0.06/0.23	−7.27/0.08	0.29/0.86	2.39/0.87
EPU125$_{\mathrm{Cc}}$	−0.02/0.24	−4.21/0.05	0.08/0.90	1.92/0.90
EPU125$_{\mathrm{Vc}}$	−0.09/0.27	−2.44/0.04	0.40/0.99	1.67/0.99
EPU125$_{\mathrm{apCc}}$	−0.01/0.25	−4.44/0.06	0.07/0.91	1.96/0.91
EPU125$_{\mathrm{apVc}}$	−0.09/0.27	−2.44/0.04	0.40/0.99	1.67/0.99
MPW80	0.00/0.11	−0.65/−0.08	0.01/0.59	0.92/0.59
EPU62$_{\mathrm{H}}$	0.02/0.06	−0.22/−0.02	0.08/0.26	0.63/0.26
EPU62$_{\mathrm{C}}$	−0.06/0.09	0.37/−0.02	0.29/0.37	0.42/0.38
EPU62$_{\mathrm{V}}$	−0.10/0.10	0.62/−0.02	0.48/0.44	0.46/0.44
EPU62$_{\mathrm{paC}}$	0.00/0.08	−0.27/−0.02	0.01/0.35	0.71/0.36
EPU62$_{\mathrm{paV}}$	−0.10/0.10	0.62/−0.02	0.48/0.44	0.46/0.44
EPU71$_{\mathrm{H}}$	0.02/0.06	−0.32/−0.02	0.11/0.28	0.69/0.29
EPU71$_{\mathrm{C}}$	−0.08/0.11	0.51/−0.02	0.41/0.48	0.49/0.48
EPU71$_{\mathrm{V}}$	−0.14/0.14	0.93/−0.03	0.69/0.60	0.63/0.61
EPU71$_{\mathrm{paC}}$	0.00/0.10	−0.49/−0.02	0.00/0.45	0.85/0.45
EPU71$_{\mathrm{paV}}$	−0.14/0.14	0.93/−0.03	0.69/0.60	0.63/0.61

[a] ap stands for anti-parallel
[b] c stands for correction

TABLE I: Tune shift and standard deviation of the beta beat at each BPM in a storage ring with an insertion device. The quantities are computed before applying the correction and after performing the correction (cor). The tune shifts have been compared with those in [3] showing a perfect agreement.

ID	$\Delta Q^{14\mathrm{Q}}_{\mathrm{cor}}$ (10^{-5})	$\Delta Q^{14\mathrm{Q}}_{\mathrm{min}}$ (10^{-5})	$\Delta\beta/\beta^{14\mathrm{Q}}_{\mathrm{cor}}$ (%)	$\Delta\beta/\beta^{14\mathrm{Q}}_{\mathrm{min}}$ (%)
SCW31	−6.12/ − 1.19	−3.02/1.15	1.66/2.07	0.04/2.09
IVU20	−0.56/ − 0.03	−1.26/0.16	0.56/0.57	0.01/0.56
IVU21	−0.06/ − 0.01	−0.55/0.05	0.24/0.28	0.00/0.28
IVU21	−0.06/ − 0.02	−0.56/0.05	0.24/0.29	0.00/0.29
EPU125$_{\mathrm{H}}$	−1.54/ − 0.06	−2.81/0.03	1.59/0.25	1.40/0.25
EPU125$_{\mathrm{C}}$	5.52/ − 0.88	3.19/1.96	2.42/2.29	2.74/2.31
EPU125$_{\mathrm{V}}$	35.34/ − 4.57	21.87/7.88	5.77/4.15	6.81/4.28
EPU125$_{\mathrm{apC}}$ [a]	5.07/ − 0.84	2.90/1.90	2.34/2.26	2.65/2.27
EPU125$_{\mathrm{apV}}$	35.34/ − 4.57	21.87/7.88	5.77/4.15	6.81/4.28
EPU125$_{\mathrm{Hc}}$ [b]	−1.73/ − 0.06	−2.22/0.27	0.94/0.86	0.29/0.86
EPU125$_{\mathrm{Cc}}$	−1.00/ − 0.06	−1.59/0.30	0.73/0.90	0.08/0.90
EPU125$_{\mathrm{Vc}}$	−0.40/ − 0.08	−1.07/0.36	0.71/0.99	0.40/0.98
EPU125$_{\mathrm{apCc}}$	−1.05/ − 0.07	−1.63/0.31	0.75/0.91	0.07/0.91
EPU125$_{\mathrm{apVc}}$	−0.40/ − 0.08	−1.07/0.36	0.71/0.99	0.40/0.98
MPW80	−0.18/ − 0.06	−0.81/0.09	0.36/0.59	0.01/0.58
EPU62$_{\mathrm{H}}$	−0.13/ − 0.01	−0.61/0.03	0.25/0.26	0.08/0.26
EPU62$_{\mathrm{C}}$	0.33/0.00	−0.07/0.07	0.28/0.38	0.29/0.37
EPU62$_{\mathrm{V}}$	0.62/0.01	0.24/0.09	0.43/0.44	0.48/0.44
EPU62$_{\mathrm{paC}}$	−0.09/ − 0.01	−0.63/0.05	0.27/0.35	0.01/0.35
EPU62$_{\mathrm{paV}}$	0.62/0.01	0.24/0.09	0.43/0.44	0.48/0.44
EPU71$_{\mathrm{H}}$	−0.17/ − 0.01	−0.68/0.04	0.28/0.29	0.11/0.28
EPU71$_{\mathrm{C}}$	0.48/0.00	0.01/0.10	0.38/0.48	0.40/0.48
EPU71$_{\mathrm{V}}$	0.96/0.00	0.43/0.15	0.61/0.61	0.69/0.60
EPU71$_{\mathrm{paC}}$	−0.14/ − 0.01	−0.75/0.08	0.32/0.45	0.00/0.45
EPU71$_{\mathrm{paV}}$	0.96/0.00	0.43/0.15	0.61/0.61	0.69/0.60

[a] ap stands for anti-parallel
[b] c stands for correction

TABLE II: Tune shift and standard deviation of the beta beat at each BPM in a storage ring with an insertion device. The quantities shown are the corresponding to a correction without beta beating minimization (cor) and with beta beating minimization (min).

with $\Delta\beta/\beta_{\text{ID}}$ column we see that its values are almost the same in most of the cases. Actually, the biggest differenece appears in the horizontal component of the EPU125_{V} and $\text{EPU125}_{\text{apV}}$ which is of about 4.5 %. This results show that the 14Q correction with a minimum introduction of beta beating works since it does not worsen the beta beating and also corrects the tune.

VII. CONCLUSIONS

At the light of these simulation result we can infer various things. First, that the assumption we did to chose the most effective pair of quadrupole families to correct the tune actually works. We show this studying Figs. 3 (last row) 5 and 6 which presented peaks in the quadrupole strengths in those quadrupole families that form the biggests areas the shifted-tune space, see Fig. 1. Second, that the three different proposed correction methods, *i.e.* 2Q, 11Q and 14Q, also work since they correct the tune when different type of errors are introduced in the storage ring. Particularly, we saw through the 14Q method that a correction can be performed without worsen the beta beating if a contraint of minimizing the change of the beta function introduced.

[1] E. D. Courant and H. S. Snyder, *Theory of the Aternating-Gradient Synchrotron*, Ann. Phys. **281** (2000)

[2] M. Sands, *The Physics of Storage Rings, An Introduction*, U. S. Atomic Energy Commission, SLAC (1970)

[3] Z. Marti, *XAIRA's Insertion Device Effect on the ALBA Beam Dynamics*, ALBA int. report ACDIV-2017-0x (2017)

Development of a betatron tune feedback application for the ALBA storage ring

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Zeus Martí

July 2018

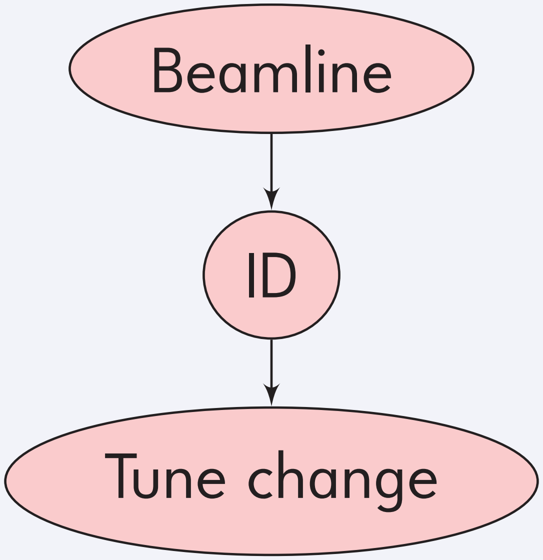
Table of Contents

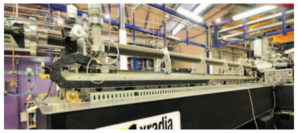
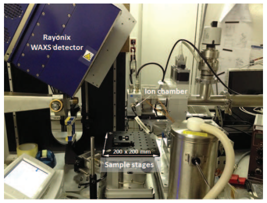
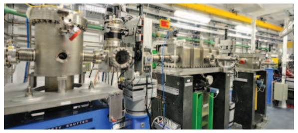
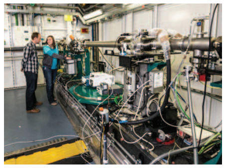
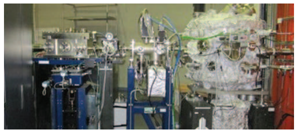
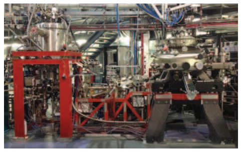
Project's goal

Currently, ALBA has
7 ID beamlines:

- MSPD
- NCD-SWEET
- XALOC
- LOREA (commissioning)
- CLÆSS
- CIRCE
- BOREAS

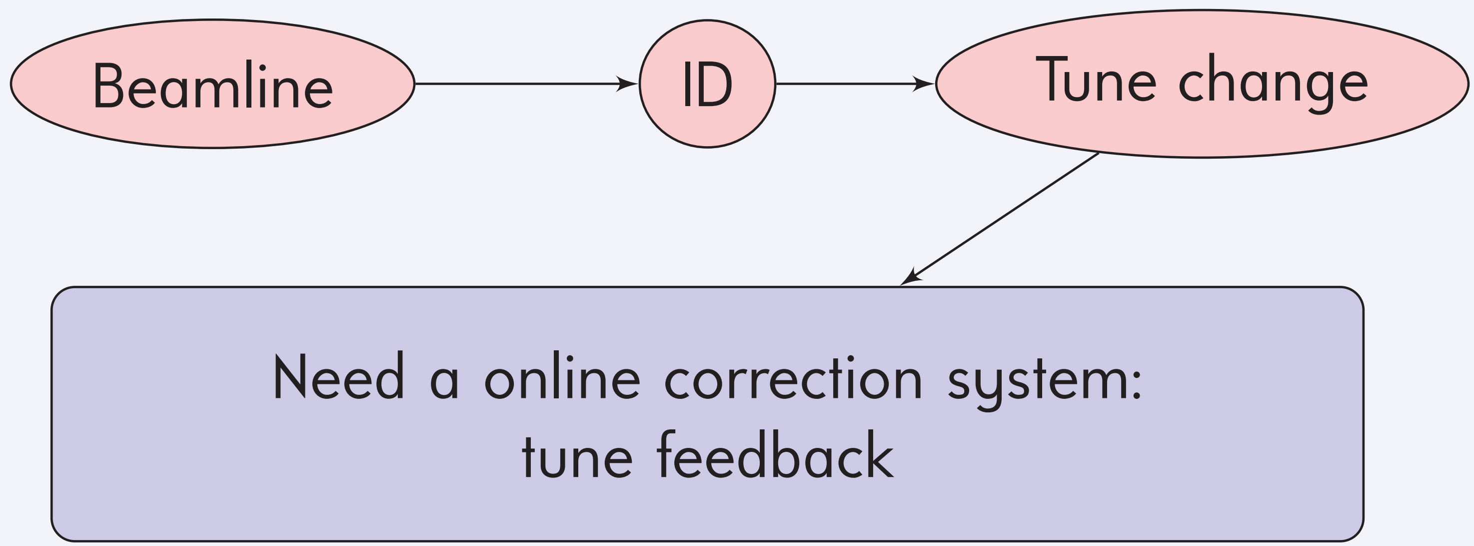
... but it has room for more beamlines.

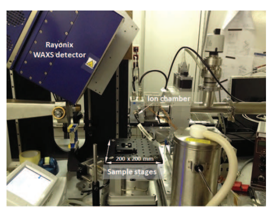
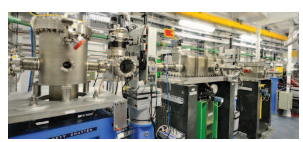
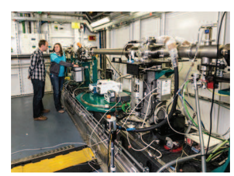
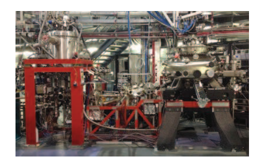


Project's goal

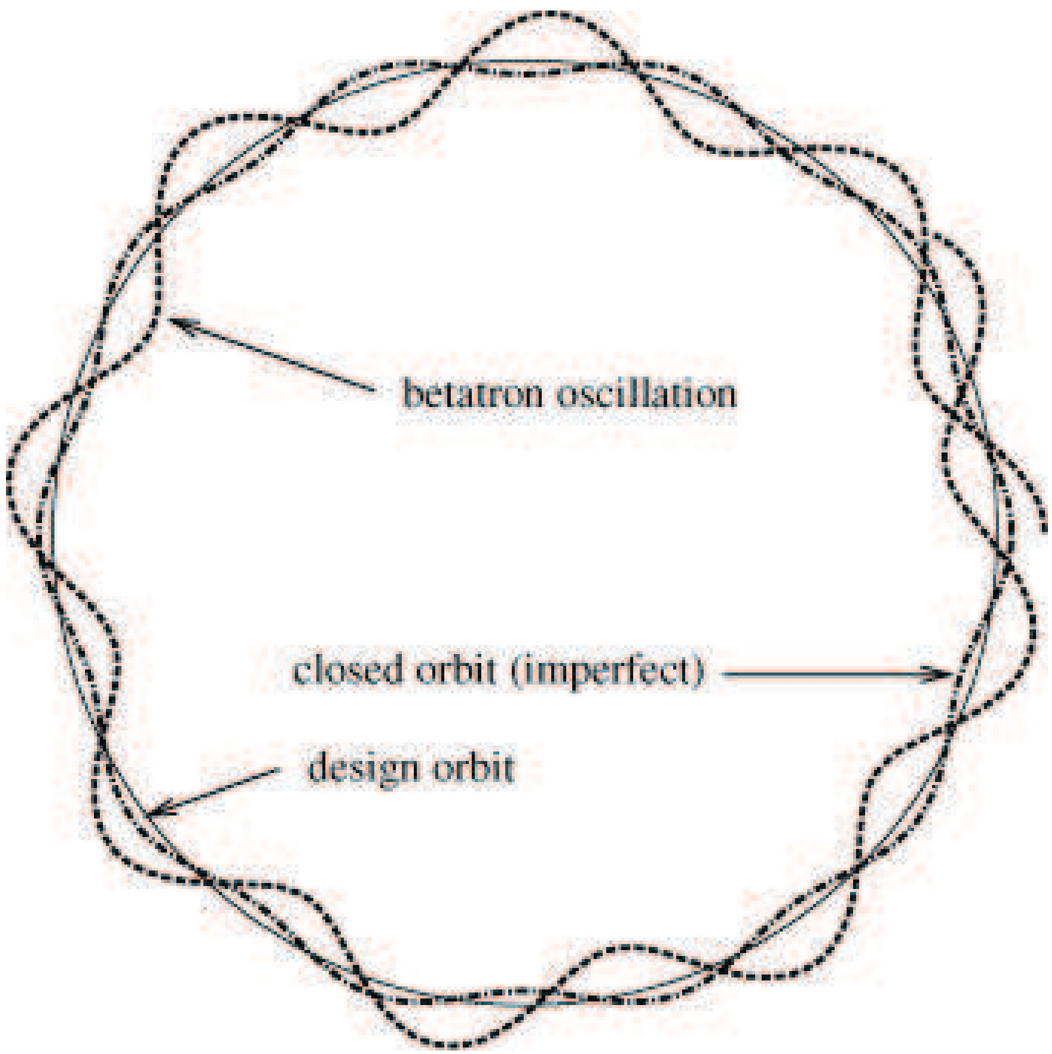
Adding IDs perturbs the beam parameters ...



The betatron tune number

Betatron tune number, or simply tune, is the number of transversal oscillations that the particles perform in one revolution.



$$Q_{x,y} = \frac{1}{2\pi} \oint \frac{\mathrm{d}s}{\beta_{x,y}(s)}$$

Correction of a global parameter: the tune

The tune can be changed varying the strength of, at least, one quadrupole.

$$\Delta Q_{x,y} = \pm \frac{1}{4\pi}\, \beta_{x,y}^{\text{quad}}\, \Delta k\, L_{\text{quad}}$$

Two unknown quantities, ΔQ_x and ΔQ_y

One variable Δk

Correction of a global parameter: the tune

The tune can be changed varying the strength of, at least, one quadrupole.

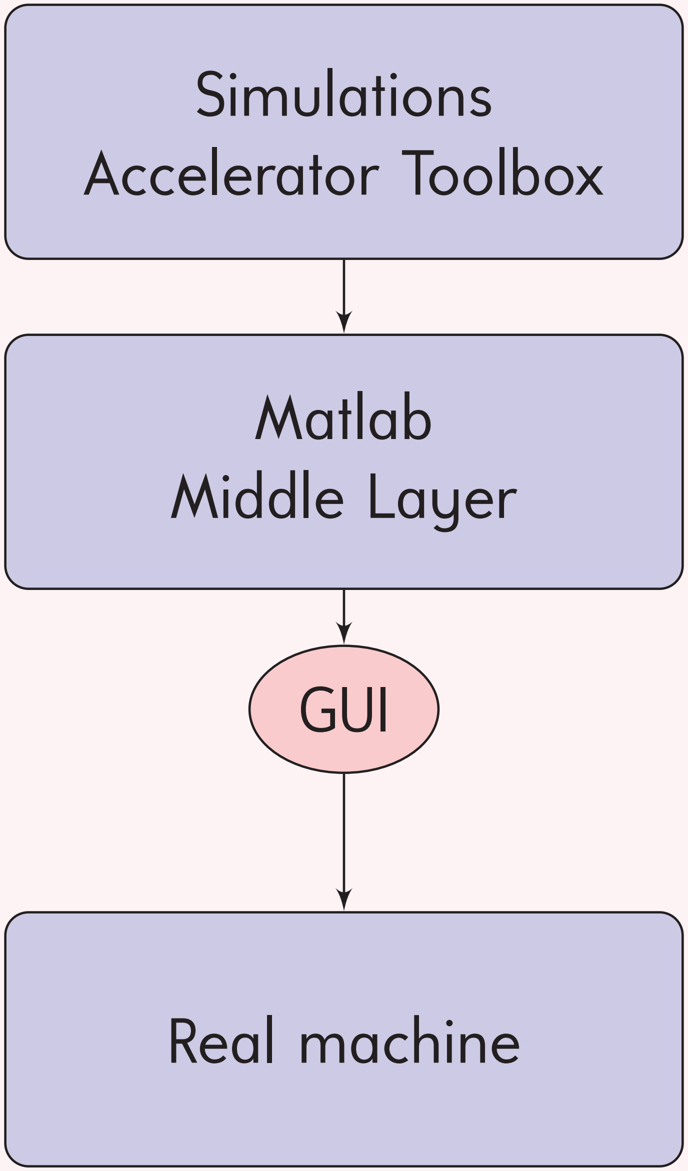
$$\Delta Q_{x,y} = \pm \frac{1}{4\pi} \beta_{x,y}^{\text{quad}} \, \Delta k \, L_{\text{quad}}$$

Two unknown quantities, ΔQ_x and ΔQ_y
One variable Δk

We need at least two quadrupoles, providing Δk_1 and Δk_2, to correct the working point.

$$\text{Working point} = (Q_x, Q_y)$$

Procedure



Simulations
Accelerator Toolbox
Matlab
Middle Layer
GUI
Real machine

2Q correction

Linear relation between ΔQ and Δk:

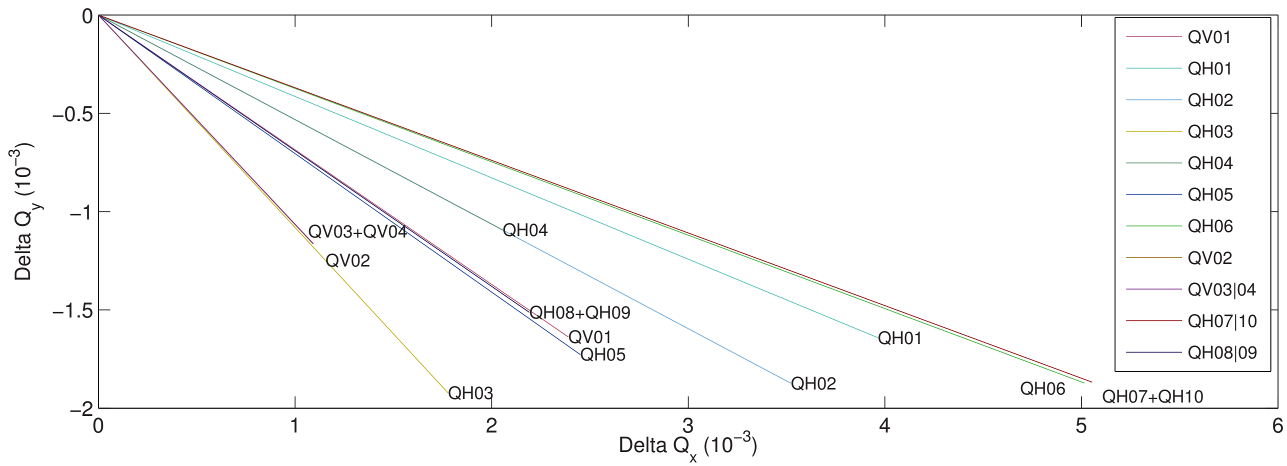
$$\Delta \mathsf{Q} = \mathsf{M}\Delta \mathsf{k}$$

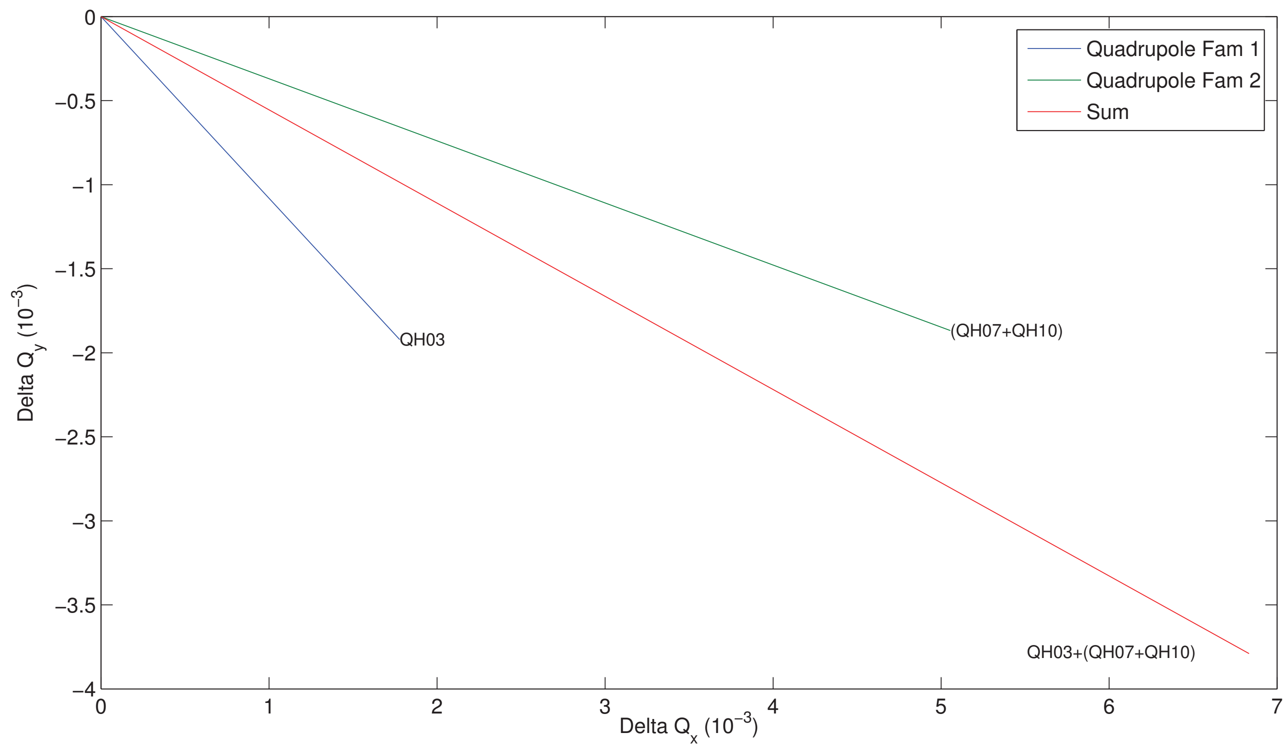
The tune response matrix:

$$\mathsf{M}_{2Q} = \frac{1}{\Delta k}\begin{pmatrix} \Delta Q_x^{(1)} & \Delta Q_x^{(2)} \\ \Delta Q_y^{(1)} & \Delta Q_y^{(2)} \end{pmatrix}$$

The correction to apply to the quadrupoles:

$$\Delta \mathsf{k}_{cor} = -\mathsf{M}_{2Q}^{-1}\Delta \mathsf{Q}_{meas}$$


Delta Qy (10^-3)
Delta Qx (10^-3)
QV01
QH01
QH02
QH03
QH04
QH05
QH06
QV02
QV03|04
QH07|10
QH08|09
QV03+QV04
QV02
QH04
QH08+QH09
QV01
QH05
QH01
QH02
QH03
QH06
QH07+QH10


Delta Qy (10^-3)
Delta Qx (10^-3)
Quadrupole Fam 1
Quadrupole Fam 2
Sum
QH03
(QH07+QH10)
QH03+(QH07+QH10)

11Q correction: preserving lattice symmetry

The tune response matrix of 11Q:

$$M_{11Q} = \frac{1}{\Delta k} \begin{pmatrix} \Delta Q_x^{(1)} & \cdots & \Delta Q_x^{(11)} \\ \Delta Q_y^{(1)} & \cdots & \Delta Q_y^{(11)} \end{pmatrix}$$

But M_{11Q} is not square $\rightarrow$ SVD method

$$M_{11Q} = USV^T$$
$$M_{11Q}^{-1} = VS^{-1}U^T$$

The correction:

$$\Delta k_{cor} = -M_{11Q}^{-1} \Delta Q_{meas}$$

THIS CORRECTION DŒSN'T CARE ABOUT THE BETA BEATING!

14Q correction: beta beating minimization

$$\mathrm{M}_{14Q} = \frac{1}{\Delta k} \begin{pmatrix} \Delta Q_x^{(1)} & \cdots & \Delta Q_x^{(14)} \\ \Delta Q_y^{(1)} & \cdots & \Delta Q_y^{(14)} \end{pmatrix}$$

M_{14Q} fulfills

$$\mathrm{M}_{14Q}(\Delta k_{cor} + \Delta k_{ker}) = \mathrm{M}_{14Q}\Delta k_{cor} + \mathrm{M}_{14Q}\Delta k_{ker} = \mathrm{M}_{14Q}\Delta k_{cor}$$

Δk_{ker} belongs to the kernel or null space of M_{14Q}, hence

Δk_{ker} DO NOT CHANGE THE TUNE!

14Q correction: beta beating minimization

In order to minimize the beta beating contribution of the correction Δk_{ker} must fulfil

$$\Delta k_{ker} = -\,\mathrm{ker}(M_{14Q}) M_{\beta}^{-1} \Delta\beta/\beta_{meas}$$

where

$$M_{\beta} = \frac{1}{\Delta k} \left(\frac{\Delta\beta^{(1)}}{\beta} \cdots \frac{\Delta\beta^{(12)}}{\beta} \right)$$

and

$$\Delta\beta/\beta_{meas} = \frac{\beta_{cor} - \beta_{ID}}{\beta_{ID}}$$

Simulation results

Simulations with IVU21, $EPU62_V$ and $EPU71_V$

TUNE SHIFT

ΔQ_{ID} (10^{-4})	ΔQ_{2Q} (10^{-4})	ΔQ_{11Q} (10^{-4})	ΔQ_{14Q} (10^{-4})
$-24/39$	$-0.79/-0.03$	$-0.35/-0.05$	$-0.005/-0.006$

BETA BEATING STANDARD DEVIATION

$\Delta\beta/\beta_{ID}$ (%)	$\Delta\beta_{2Q}/\beta$ (%)	$\Delta\beta_{11Q}/\beta$ (%)	$\Delta\beta_{14Q}/\beta$ (%)
$0.63/1.12$	$2.63/1.11$	$1.86/1.12$	$0.63/1.10$

Interface

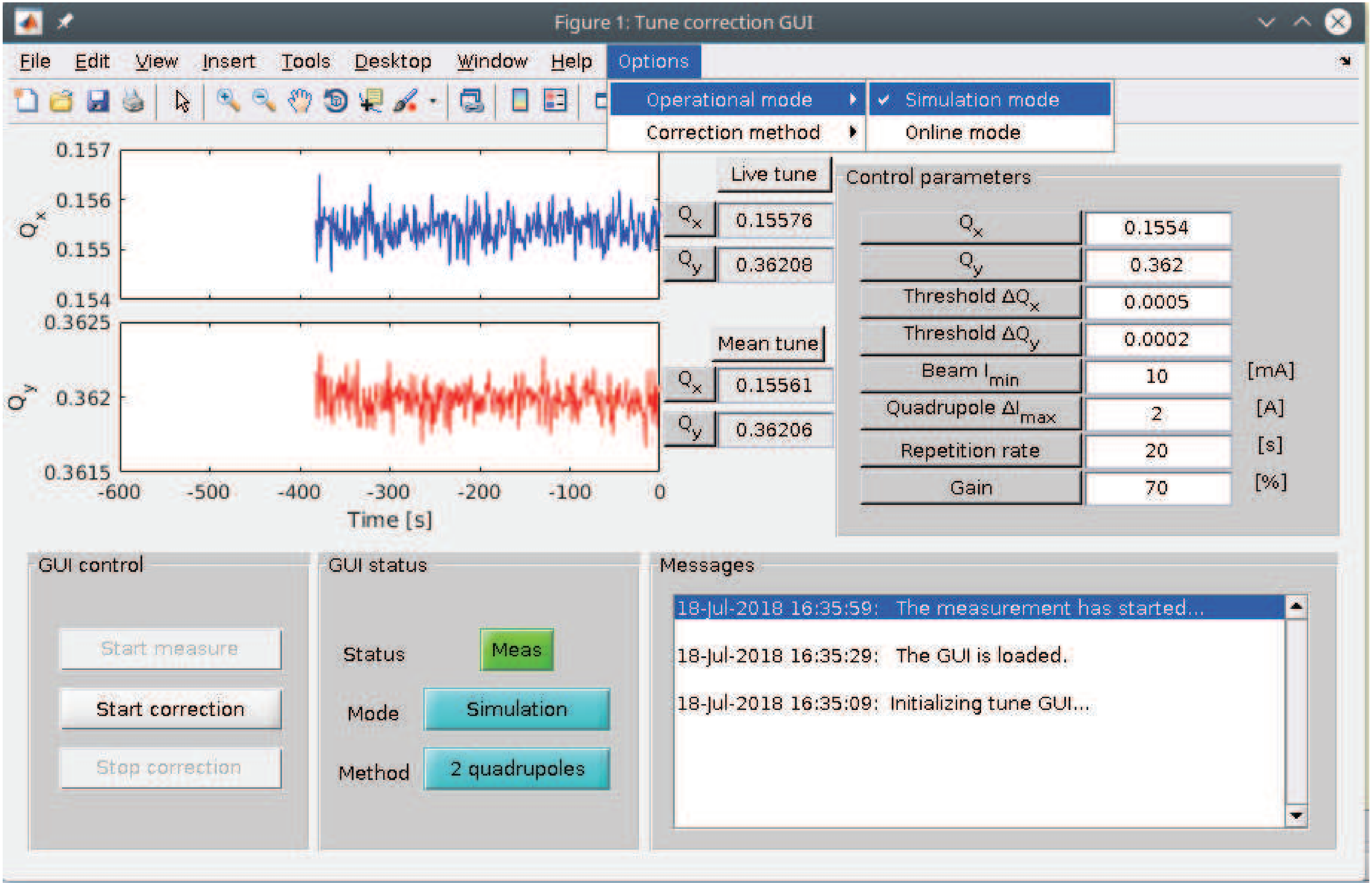


Figure 1: Tune correction GUI
File Edit View Insert Tools Desktop Window Help Options
Operational mode
Correction method
Simulation mode
Online mode
0.157
0.156
0.155
0.154
Q_x
0.3625
0.362
0.3615
Q_y
-600 -500 -400 -300 -200 -100 0
Time [s]
Live tune
Q_x 0.15576
Q_y 0.36208
Mean tune
Q_x 0.15561
Q_y 0.36206
Control parameters
Q_x 0.1554
Q_y 0.362
Threshold ΔQ_x 0.0005
Threshold ΔQ_y 0.0002
Beam I_{min} 10 [mA]
Quadrupole ΔI_{max} 2 [A]
Repetition rate 20 [s]
Gain 70 [%]
GUI control
Start measure
Start correction
Stop correction
GUI status
Status Meas
Mode Simulation
Method 2 quadrupoles
Messages
18-Jul-2018 16:35:59: The measurement has started...
18-Jul-2018 16:35:29: The GUI is loaded.
18-Jul-2018 16:35:09: Initializing tune GUI...

Interface

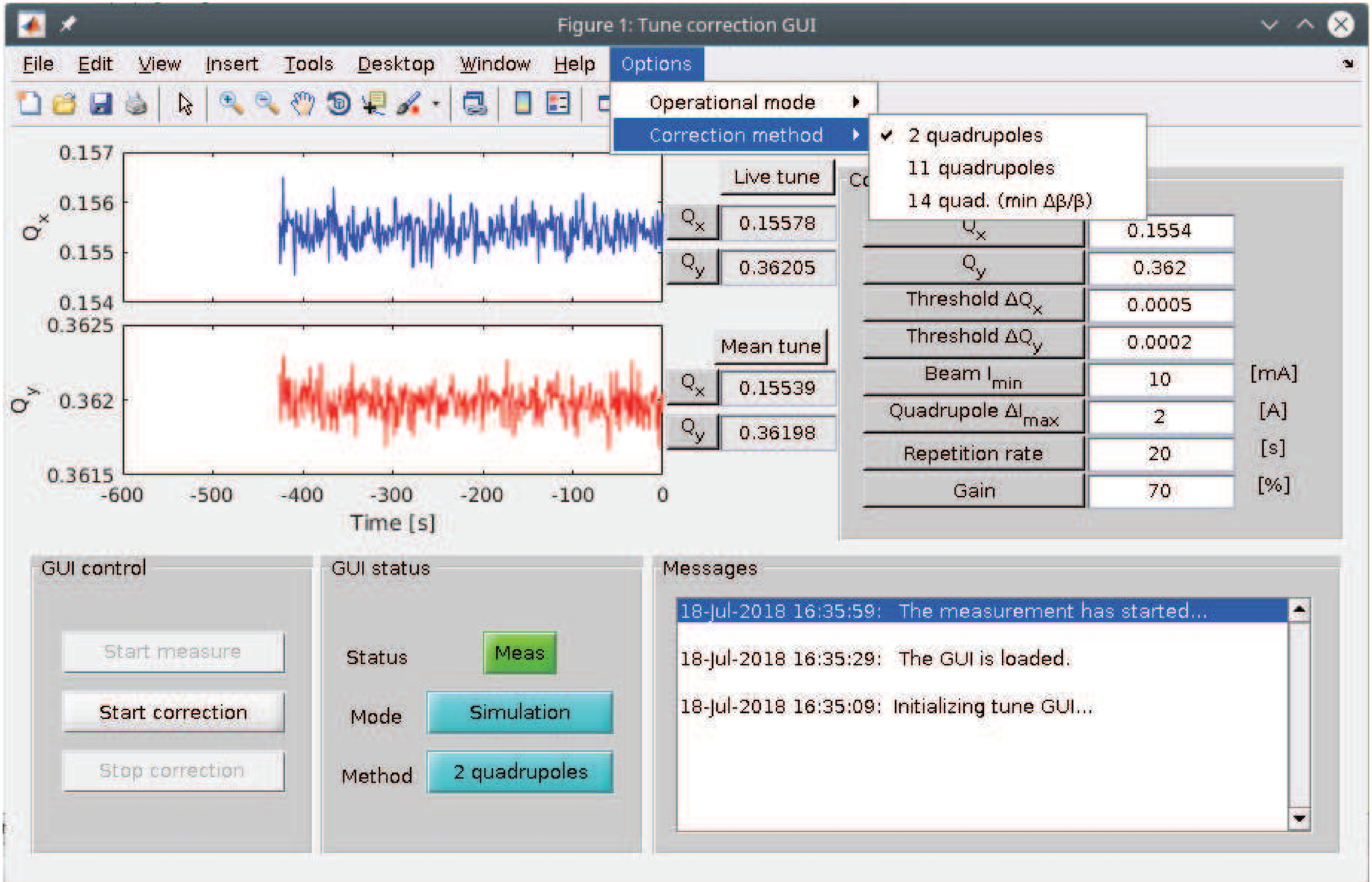
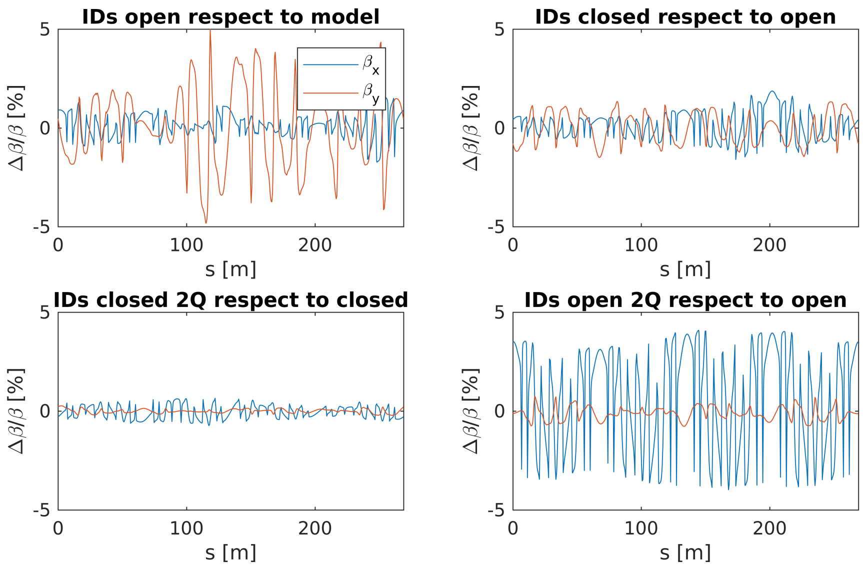
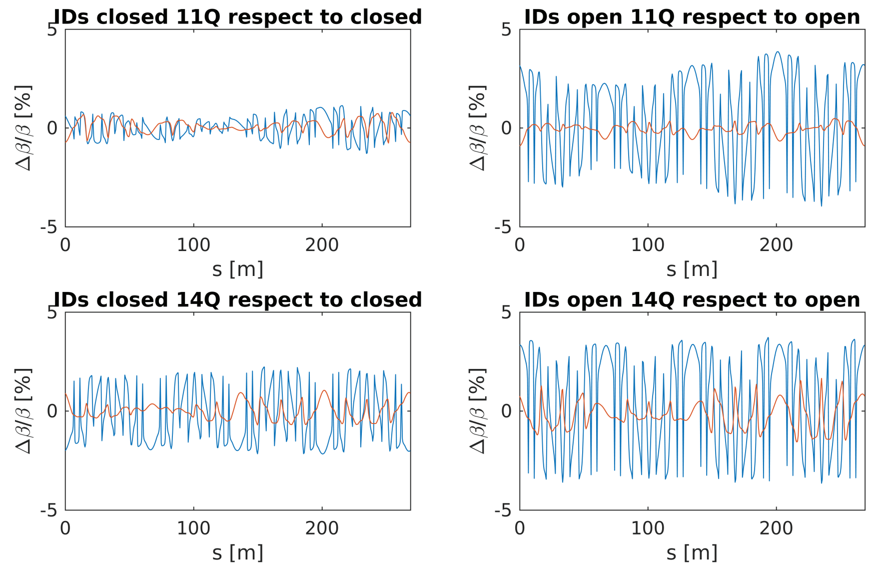


Figure 1: Tune correction GUI
File Edit View Insert Tools Desktop Window Help Options
Operational mode
Correction method
2 quadrupoles
11 quadrupoles
14 quad. (min Δβ/β)
0.157
0.156
0.155
0.154
Qx
0.3625
0.362
0.3615
Qy
-600 -500 -400 -300 -200 -100 0
Time [s]
Live tune
Qx 0.15578
Qy 0.36205
Mean tune
Qx 0.15539
Qy 0.36198
Qx 0.1554
Qy 0.362
Threshold ΔQx 0.0005
Threshold ΔQy 0.0002
Beam Imin 10 [mA]
Quadrupole ΔImax 2 [A]
Repetition rate 20 [s]
Gain 70 [%]
GUI control
Start measure
Start correction
Stop correction
GUI status
Status Meas
Mode Simulation
Method 2 quadrupoles
Messages
18-Jul-2018 16:35:59: The measurement has started...
18-Jul-2018 16:35:29: The GUI is loaded.
18-Jul-2018 16:35:09: Initializing tune GUI...

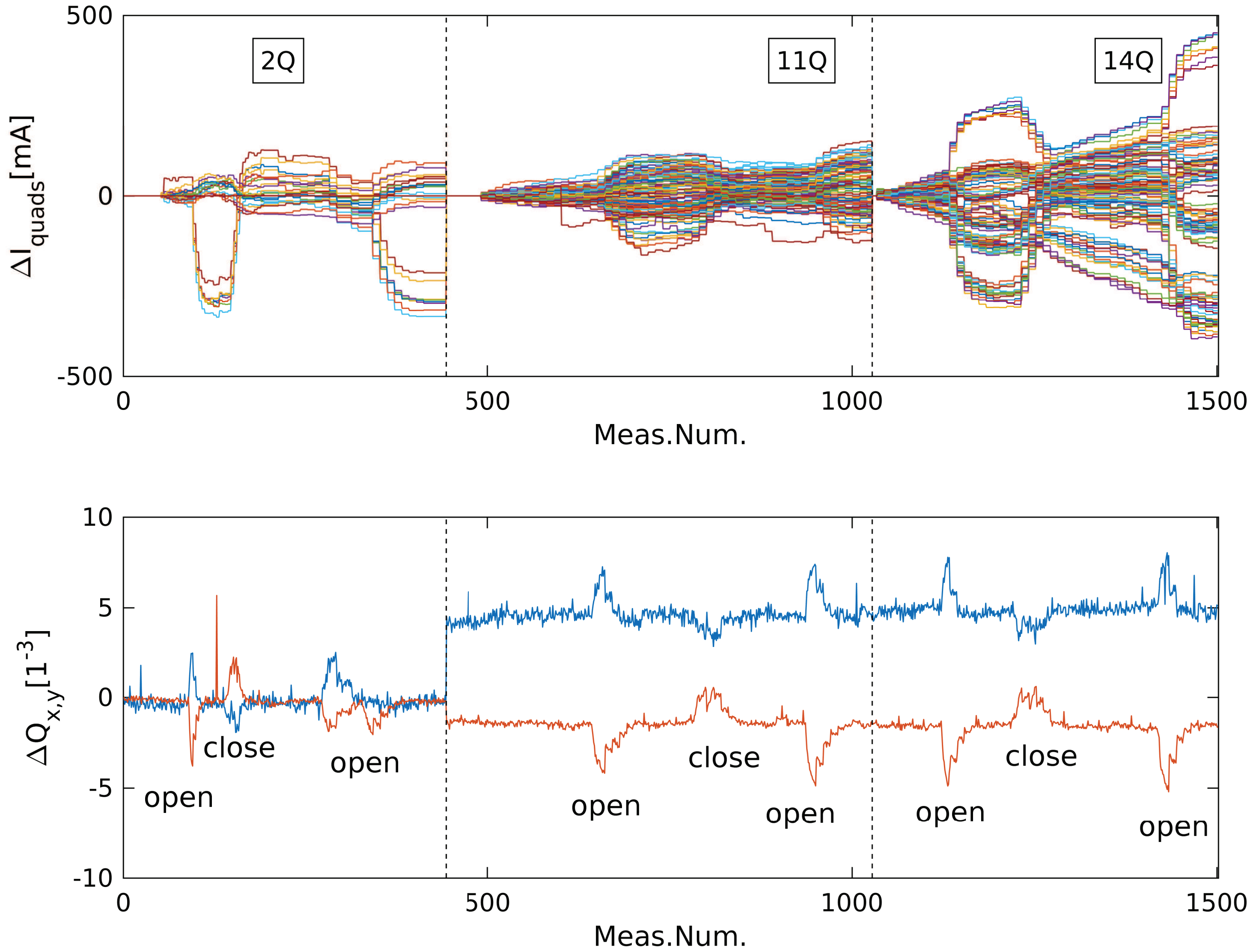
First experiment: Beta beating measures



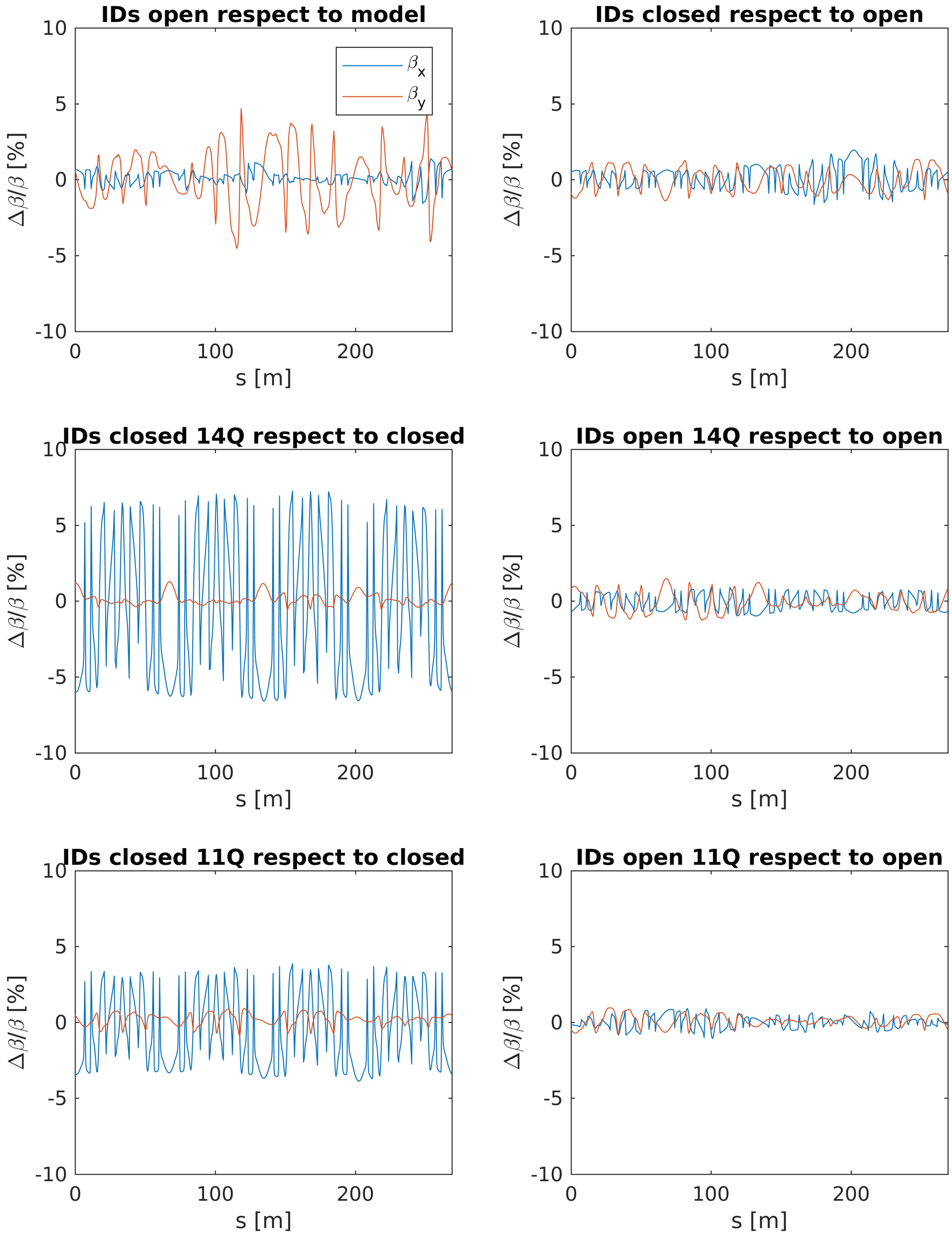


We measured a beta beating with the 14Q method as large as the 2Q where we expected the lower modification of the beta beating using the 14Q method.

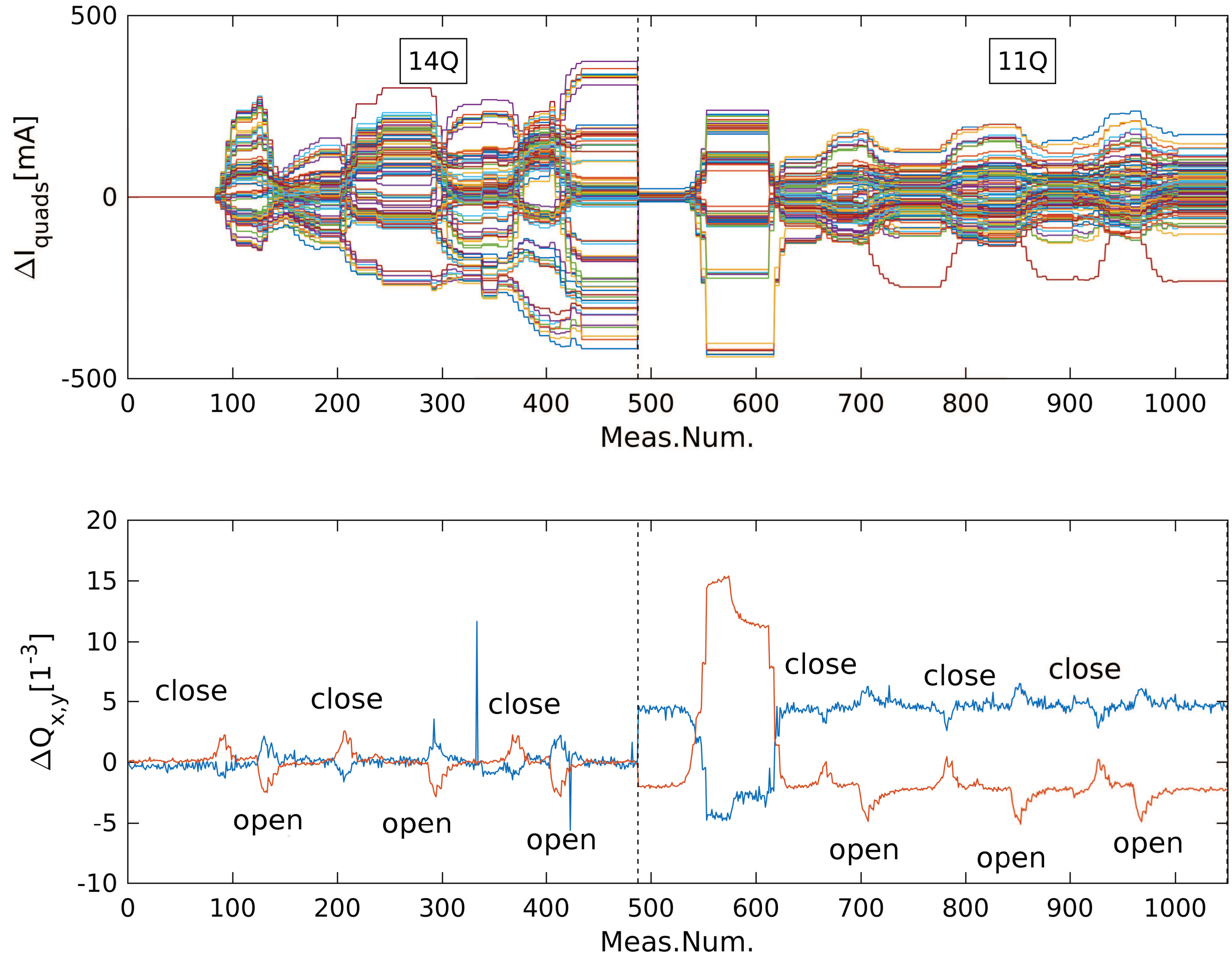
First experiment: Quadrupole intensities measures



The 14Q method produced a huge drift in the qudrupoles.


IDs open respect to model
IDs closed respect to open
IDs closed 14Q respect to closed
IDs open 14Q respect to open
IDs closed 11Q respect to closed
IDs open 11Q respect to open
β_x
β_y
$\Delta\beta/\beta$ [%]
s [m]
10
5
0
-5
-10
0
100
200

Second experiment: Quadrupole intensities measures



We recovered the same results as in the first experiment.

Conclusions

1. The simulations results show the expected behaviour: the correction of the tune and beta beating minimization with 14Q method works.

2. The experiments show that:
   - the tune is indeed corrected but the beta beating minimization with the 14Q method is affected by the correction.
   - 14Q correction produces a drift in the quadrupoles.

A SOLUTION TO THIS ISSUE MUST BE FOUND!