Mechanical alignment based on Beam Diagnostics

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Introduction

The policy at ESRF is to perform periodic realignments to keep reasonably good geometry of the machine.

All corrections on the beam are performed with magnetic correctors. However, we explored different ways to introduce a mechanical correction before using the magnetic correctors.

Expected consequences may be:

- A reduction of the strength of correctors
  (not crucial since we are far from their maximum)
- The minimisation of the consequences of a corrector failure
- An improvement the residual value after correction

Summary

- Magnetic field errors, consequences on the beam
- How are alignment errors related to these field errors
- Corrections test
  - Vertical closed orbit
  - Coupling

Errors and consequences

Only magnetic field errors can affect the trajectory of particles

Type of error		Effect on the beam	Diagnostic
Beam Deviation	H	H closed orbit distortion	H Beam position monitors
	V	V closed orbit distortion	V Beam position monitors
Focusing		Tune change	Tune measurement
		Beam size modulation	Beam size measurement
		Dispersion modulation	Dispersion measurement
Coupling		Vertical emittance	Beam size measurement Orbit cross-talk
		Vertical dispersion	Dispersion measurement

Diagnostics

- Beam position monitors (BPM): Simple, Fast, large number, good resolution (1µm).
- Tune measurement: Simple, Fast, good resolution, but it is only an integral measurement.
- Beam size measurement: Complex (image processing), Fast, only 2 sensors.
- Dispersion measurement: Simple, slow, moderate resolution

How are alignment errors related to beam effects

Magnet	motion	H orbit	V orbit	Focusing	Coupling
Dipole	H translation	0	0	0	0
	V translation	0	0	Eps	0
	tilt	Eps	1	0	0
Quadrupole	H translation	1	0	0	0
	V translation	0	1	0	0
	Tilt	0	0	Eps	1
Sextupole	H translation	Eps	0	1	0
	V translation	Eps	0	0	1

Dipole alignment is not critical (except for tilt).

Horizontal motions would be too tedious since they are not motorised.

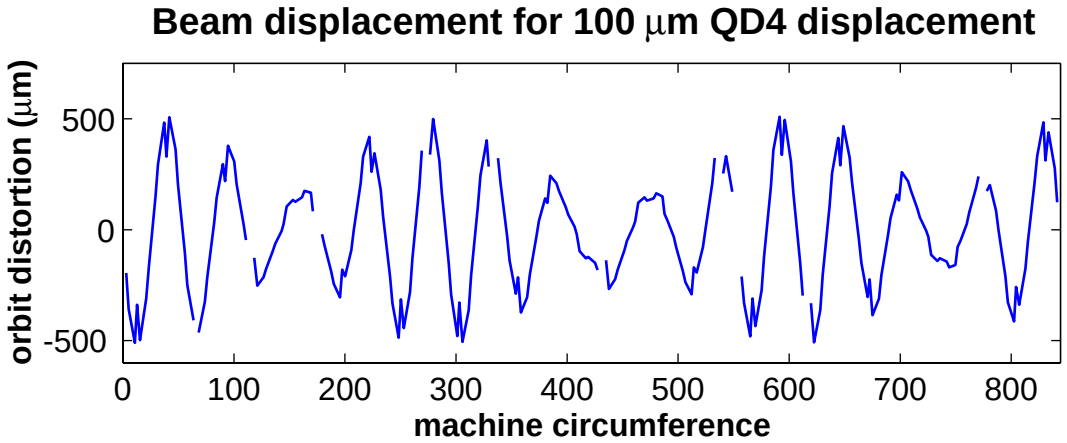
So we worked on three types of motion:

- Quadrupole vertical displacement
- Quadrupole tilt
- Sextupole vertical displacement

Vertical girder displacement

Displacement of a single quadrupole

- The modelling of such effects is easy: the displacement z_{bq} on BPM b induced by the displacement of quadrupole q is proportional the integrated strength of the quadrupole and to the displacement z_q.



- The beam is equally displaced around the circumference
- There is a large amplification factor
  (rms. beam displacement/quadrupole motion)

Response matrix

The contributions from several displacements can be linearly added. The contribution of each quadrupole to each BPM is summarised in a “response matrix”.

Individual quadrupoles

This is represented by a transfer matrix $\mathbf{T}$ such that:

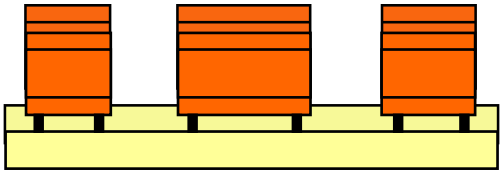
$$\mathbf{Z}_b = \mathbf{T}_q \cdot \mathbf{Z}_q$$

With $$\mathbf{Z_b} = \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_{224} \end{pmatrix}$$ beam displacement

And $$\mathbf{Z_q} = \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_{320} \end{pmatrix}$$ quadrupole displacement

Such a response matrix can be measured or built from a model. For mechanical motion, we used only theoretical matrices.

Girder translations



In fact, the quadrupoles are rigidly positioned on girders (3 or 4 quadrupoles) while the girder itself is motorised. The equation is modified to show the effect of translating the girders:

$$\mathbf{Z_b} = \mathbf{T_q} \cdot \mathbf{G_t} \cdot \mathbf{Z_g}$$

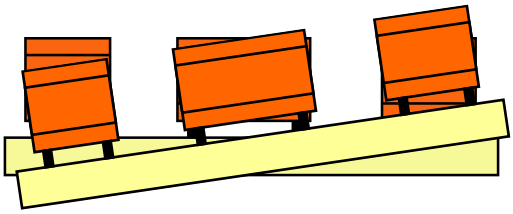
The individual displacements of the quadrupoles are related to the girder displacements $\mathbf{Z_g}$ by the matrix

$$\mathbf{G_t} = \underbrace{\begin{pmatrix} 1 & 0 & \dots & 0 \\ 1 & 0 & \ddots & 0 \\ 1 & 0 & \ddots & \vdots \\ 0 & 1 & \ddots & 1 \\ \vdots & \ddots & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{96 \text{ columns}} \Bigg\} 320 \text{ lines}$$

- The number of independent variables is reduced from 320 to 96.
- The behaviour is similar to the individual displacement case, with the following change:
  - The amplification is much smaller (quadrupoles with opposite sign on the same girder compensate)

As the efficiency of this correction looked too small, we tried rotating the girders.

Girder rotations



The orbit response to girder rotation can be written as:

$$\mathbf{Z_b} = \mathbf{T_q} \cdot \mathbf{G_r} \cdot \theta_g$$

The individual displacements of the quadrupoles are related to the girder displacements $\mathbf{Z_g}$ by the matrix

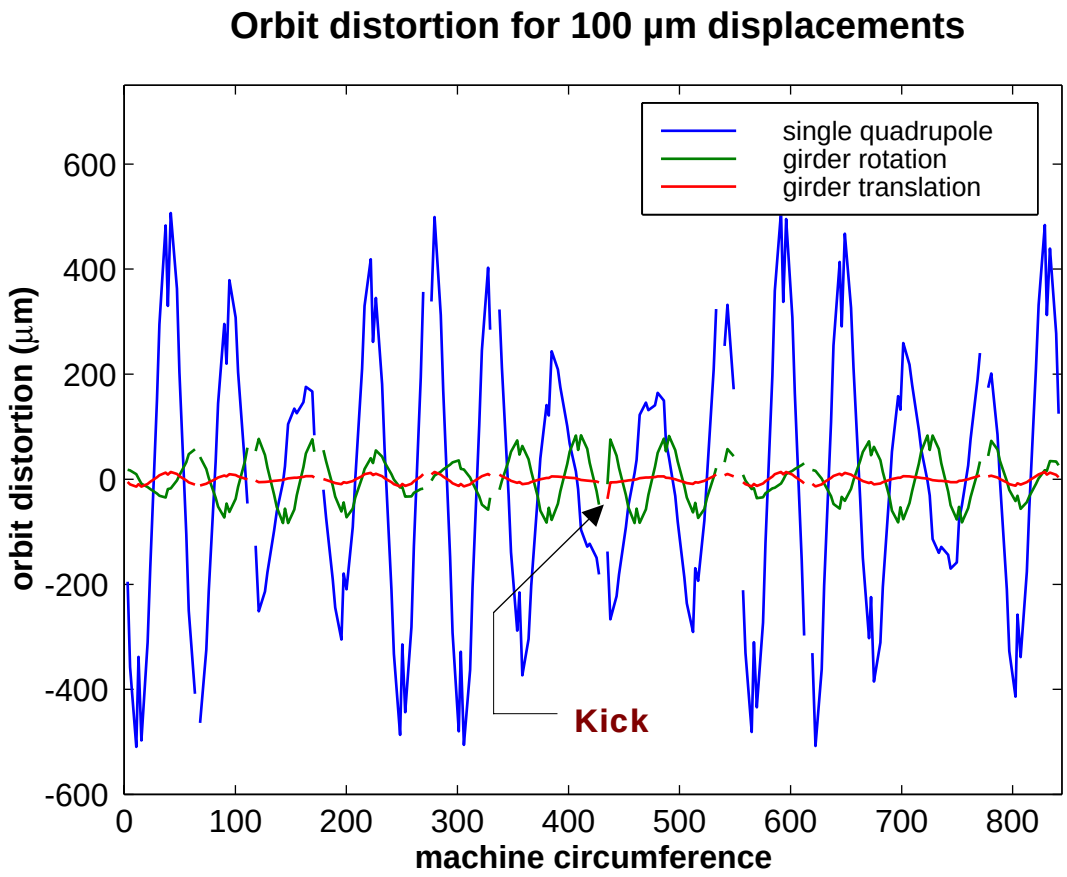
$$\mathbf{G_r} = \underbrace{\left.\begin{pmatrix} -l/2 & 0 & \dots & 0 \\ 0 & 0 & \ddots & 0 \\ l/2 & 0 & \ddots & \vdots \\ 0 & -l/2 & \ddots & -l/2 \\ \vdots & \ddots & 0 & 0 \\ 0 & 0 & 0 & l/2 \end{pmatrix}\right\} 320 \text{ lines}}_{96 \text{ columns}}$$

Individual jack motion

To have more degrees of freedom, we also considered moving independently the jacks at the extremities of the girders (The third one being adjusted to avoid any lateral tilt.

We then have 192 variables, but the efficiency is close to the pure rotation case.

Comparison of efficiency



Amplification factors for a single displacement:

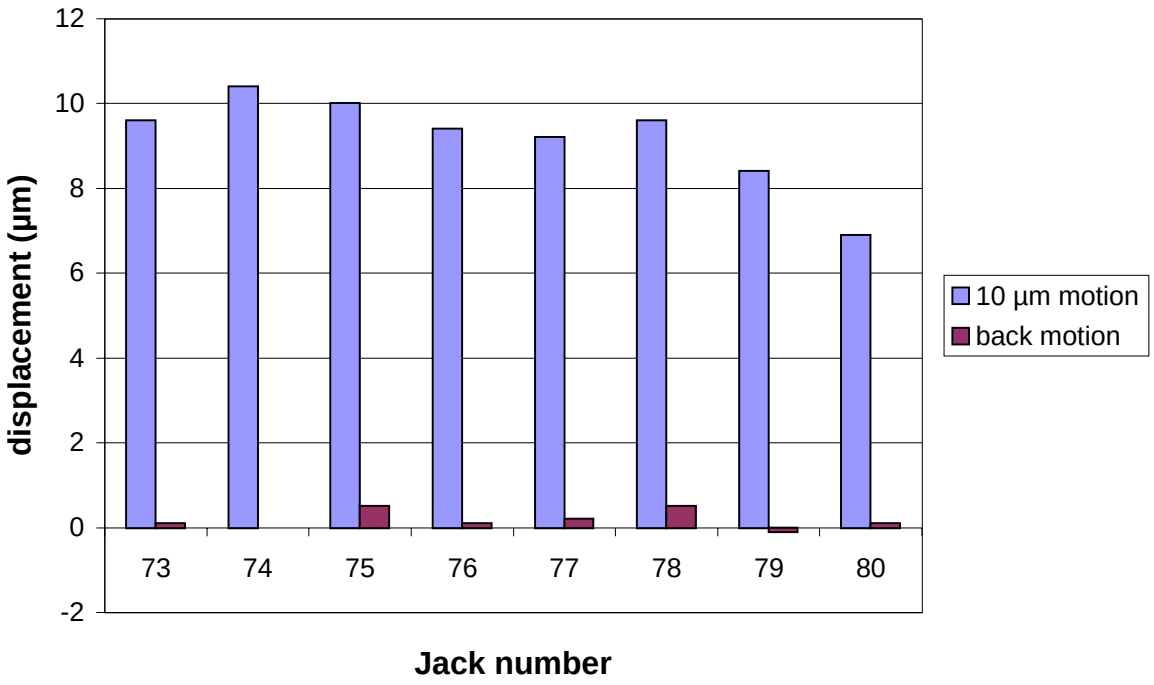
- Single quadrupole $0.2 < k < 3.5$
- Girder translation $0.070 < k < 0.90$
- Girder rotation $0.43 < k < 3.8$

Since rotations are more efficient than translations, they were used for the correction.

Calibration

We experimentally calibrated the girder motion:

A single jack is moved by 10 µm, the difference of beam orbit is measured, and fitted to the model response matrix.



- The agreement with the model is good within ± 1 µm
- The reproducibility of the initial point is also better than 1 µm

Correction algorithm

From this formulation, aligning the quadrupoles means inverting the matrix $\mathbf{R} = \mathbf{T_q} \cdot \mathbf{G_r}$.

However, there are serious problems:

Oscillation wavelength >> distance between quadrupoles

⇒ The effect of 2 adjacent quadrupoles is very similar

⇒ The matrix is ill-conditioned

The method we used is the same used for usual correction with magnetic steerers.

Solution by Singular value Decomposition

The matrix $\mathbf{R}$ can be expressed as:

$$\mathbf{R} = \mathbf{U} \cdot \mathbf{S} \cdot \mathbf{V}^{\mathrm{T}}$$

where $\mathbf{U}$ and $\mathbf{V}$ are orthogonal matrices, and $\mathbf{S}$ is diagonal.

Its pseudo-inverse is:

$$\mathbf{V} \cdot \mathbf{S}^{-1} \cdot \mathbf{U}^{\mathrm{T}}$$

So the least square solution of the system is:

$$\theta_{\mathbf{g}} = \mathbf{V} \cdot \mathbf{S}^{-1} \cdot \mathbf{U}^{\mathrm{T}} \cdot \left(-\mathbf{Z_b}\right)$$

Interpretation:

$\mathbf{V}$ is a basis of normalised orthogonal correction vectors ("Eigen corrections"):

$$\sqrt{\sum_{i=1}^{n} V_{ik}^{\ 2}} = \sqrt{96} \cdot V_{k\,rms} = 1$$

Any combination of girder motions can be represented as a resultant of such correction vectors.

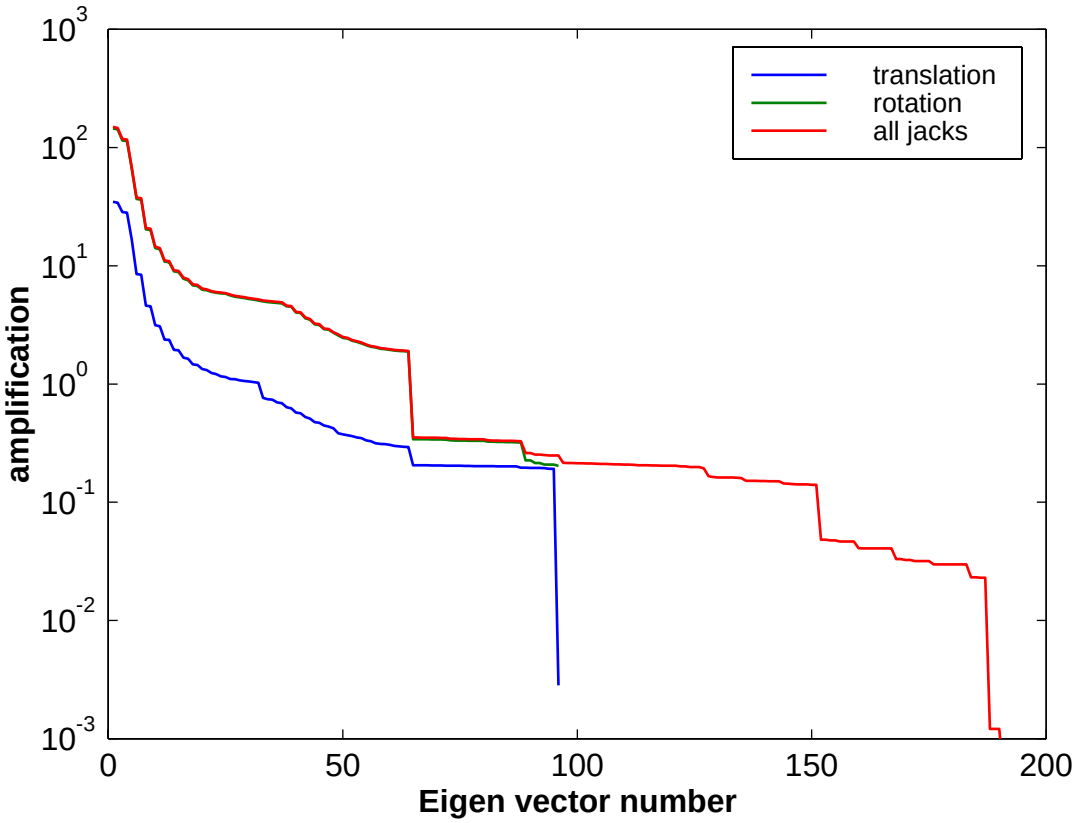
U is the corresponding set of orthogonal normalised orbits ("Eigen orbits"):

$$\sqrt{\sum_{i=1}^{m} U_{ik}^{2}} = \sqrt{224} \cdot U_{k\,rms} = 1$$

The diagonal matrix **S** indicates the "amplification" of the machine: for each Eigen correction vector:

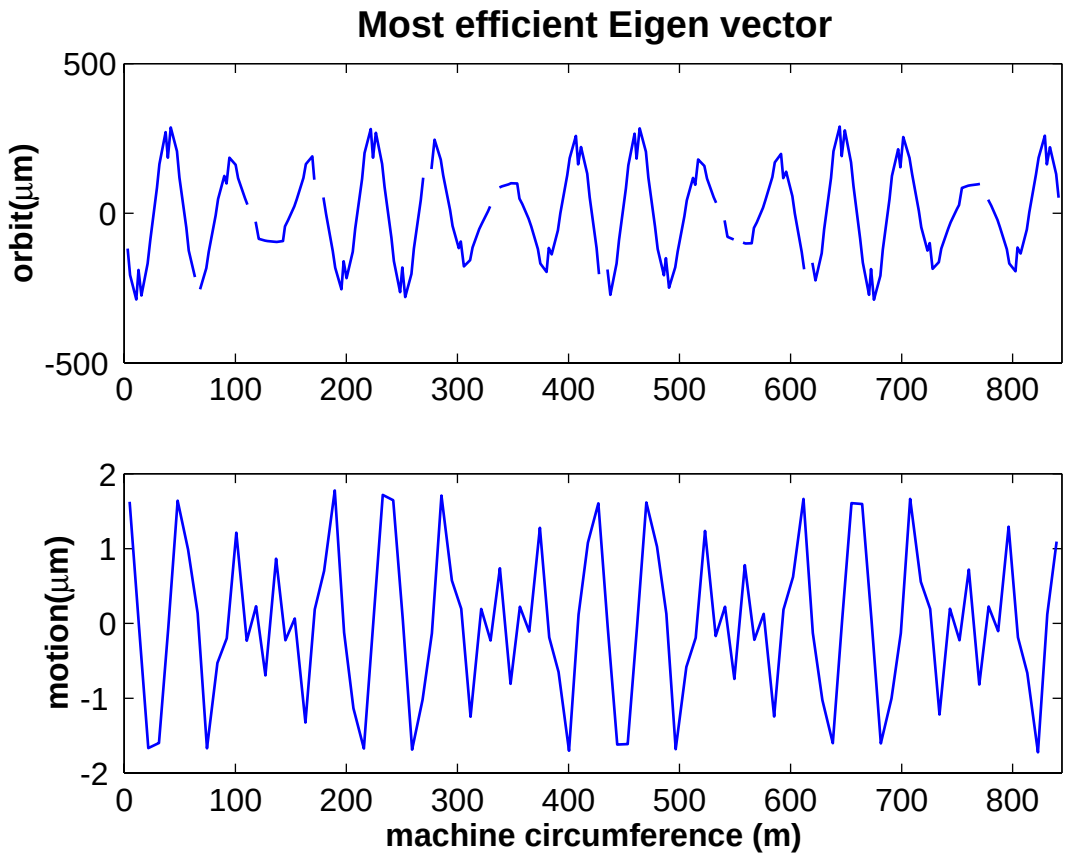
$$Z_{k\,rms} = S_k \sqrt{96/224}\; V_{k\,rms}$$

The Eigen corrections can be sorted by decreasing efficiency.



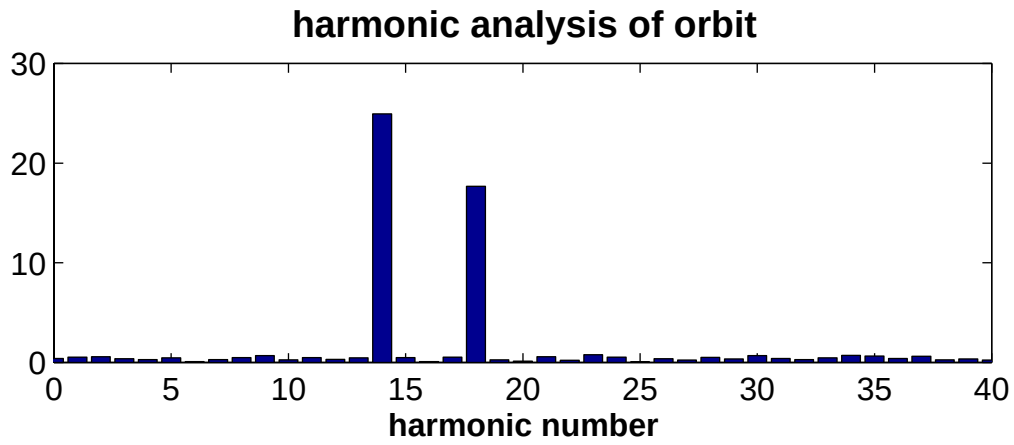
The ratio of the smallest singular value over the largest one shows the bad condition of the system of equations.

The most efficient correction vectors correspond to a harmonic excitation on the orbit. The higher sensitivity is obtained for Eigen vectors whose harmonic contents is close to the tune of the machine (ν_z =14.39 in our case)



The amplification for the first vector is

- 35 for girder translation
- 145 for girder rotation



The harmonic analysis of the first vector shows harmonic 14 + aliases

Strategy for correction

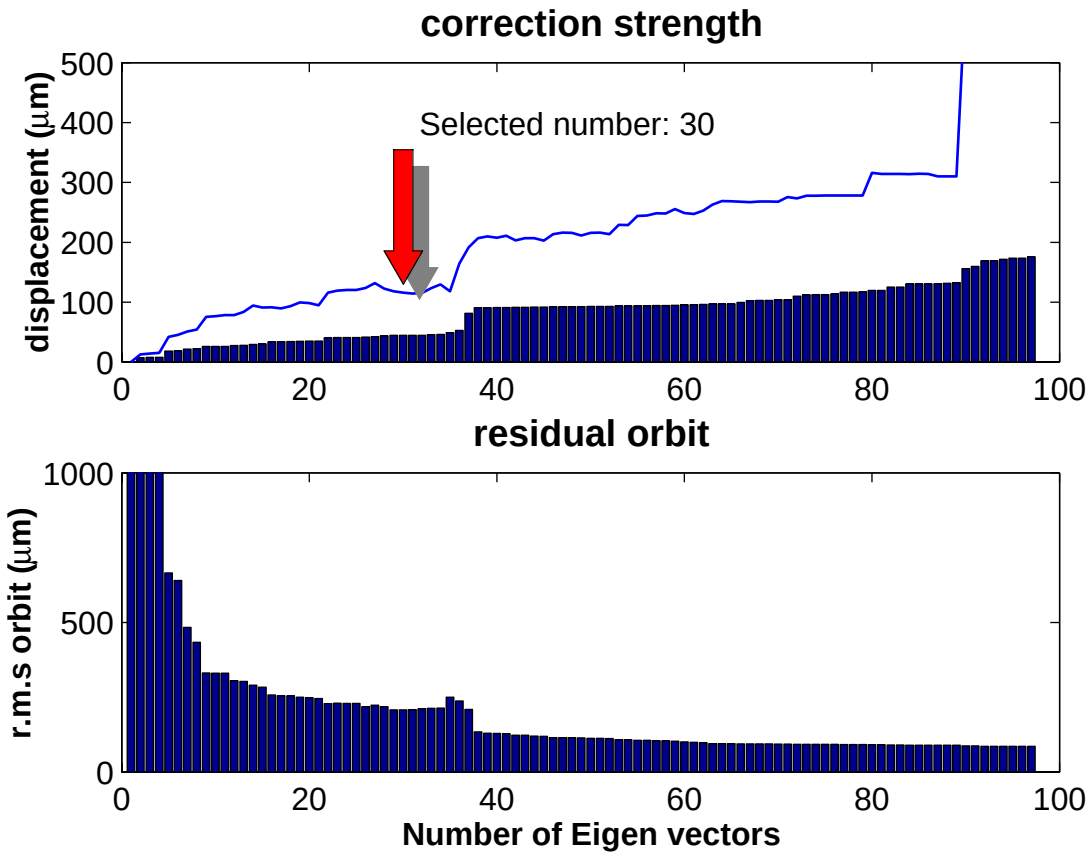
The correction can be limited to a certain number of most efficient vectors:

- This gives the major part of the correction, but uses only small displacements.
- The optimum number depends on the accuracy of the response matrix, and on the quality of the beam position measurements.

Modelling of the correction

An approximation of the uncorrected machine is obtained by measuring a standard closed orbit, and adding the opposite of the effect of the magnetic correctors.

Starting from this model, we compute the effect of a correction by rotating the girders:



From this, we decided to correct with the first 30 Eigen vectors.

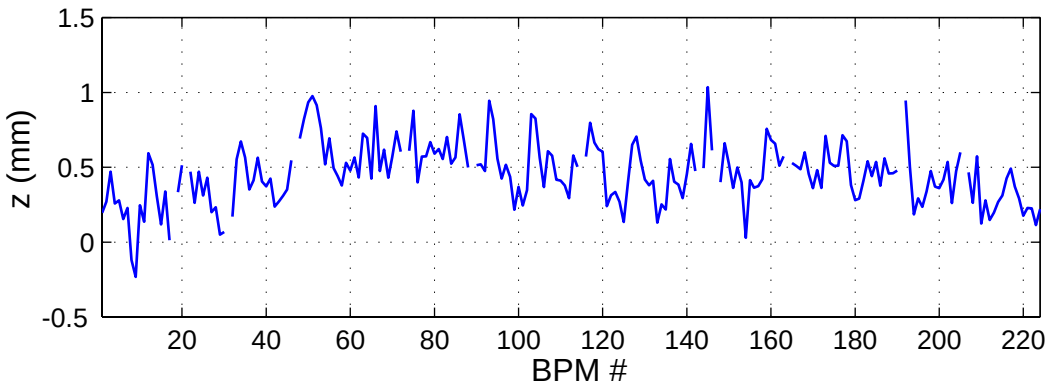
Vertical orbit correction

There is no possibility to run the machine without corrections.

So starting from the standard machine correction, the procedure was:

- Reduce the number of magnetic Eigen vectors so that the rms. orbit increases up to 500 µm
- Correct mechanically with 30 vectors,
- Iterate…

After 6 steps, we are able to switch the magnetic correctors off, with a residual orbit of 200 µm.



The final position of the girders is compatible with the accuracy of the machine survey: no obvious misalignment is introduced by the displacements.

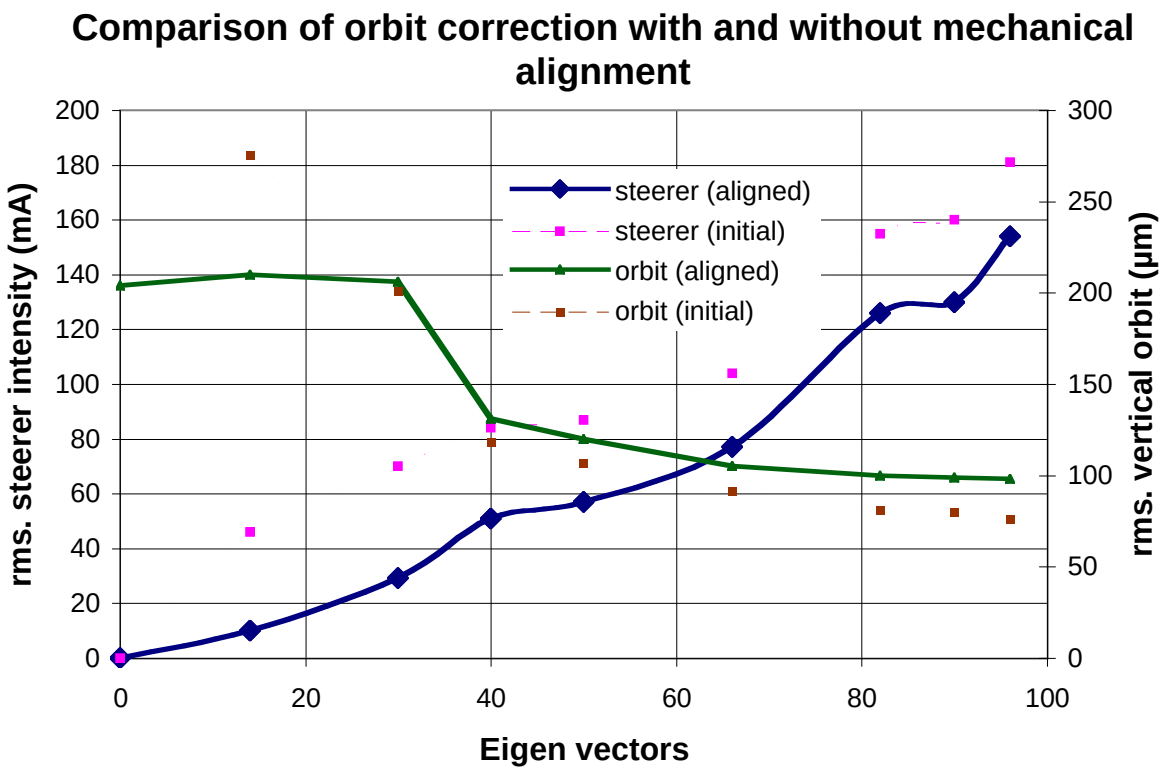
The residual orbit of 200 µm is incompatible with good performance of the machine, so the magnetic correctors were powered on top of the mechanical correction

Performance

After the realignment of the machine, all the corrections had to be done again. Results are:

	initial	realigned
Vertical rms. Orbit	91 µm	105 µm
Vertical emittance	32 pm	37 pm
Lifetime	55 h	54 h

The performance of the machine is close to the standard. However, the residual vertical orbit distortion is larger than the standard one.



Girder tilt

Tilted quadrupoles transfer the horizontal motion into the vertical plane. In a Synchrotron Radiation source, this has the consequence of increasing the vertical beam size, which otherwise would be vanishing.

The figure of merit used to quantify the tilt effect is the emittance coupling:

$$\varepsilon_z = k\,\varepsilon_x$$

Emittances are deduced from beam size measurements.

Similarly to the orbit displacement case, the sensitivity depends highly on the harmonic contents of the perturbation, the highest sensitivity being for harmonics close to the difference between horizontal and vertical tunes.

However the beam-based diagnostics are much less than for closed orbit, so that a similar correction is impossible.

In standard operation, the coupling is corrected by a set of magnetic skew quadrupole correctors.

Calibration

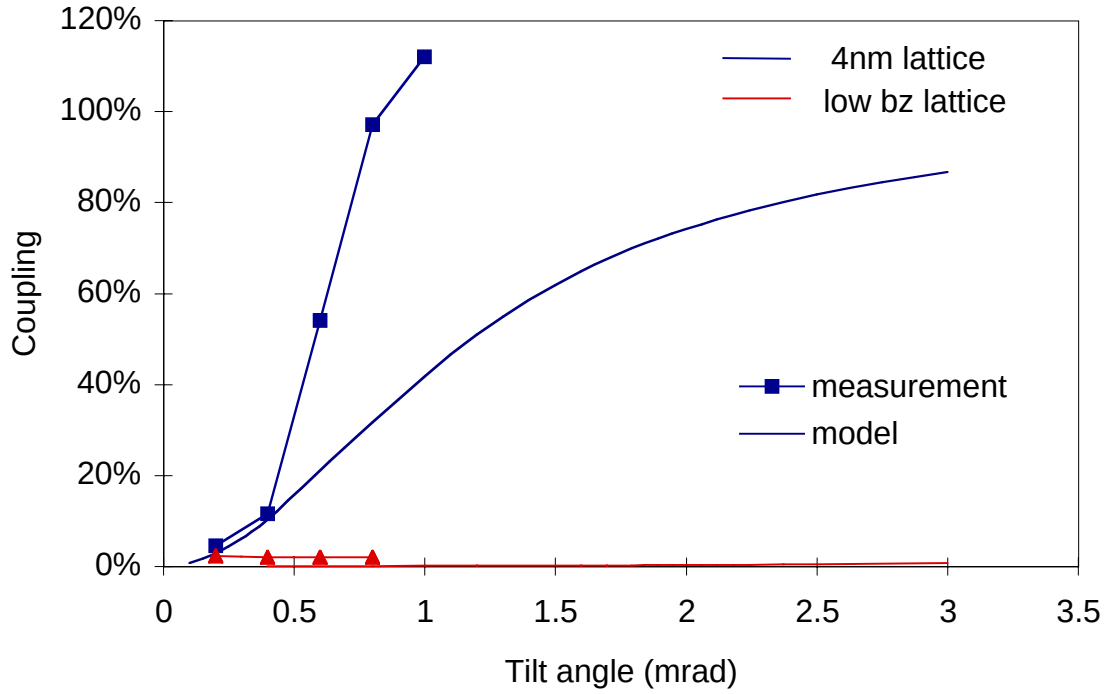
A calibration was performed by applying a harmonic tilt on the girders:

$$\theta = \hat{\theta}\cos\left(25\left(\varphi - \varphi_0\right)\right)$$

The same tilts were applied to two different optics:

- in the first one ("4nm") the excitation corresponds to the most effective harmonic,
- in the second case ("low β_z") the most effective harmonic is 22, 3 integers apart from the excitation.

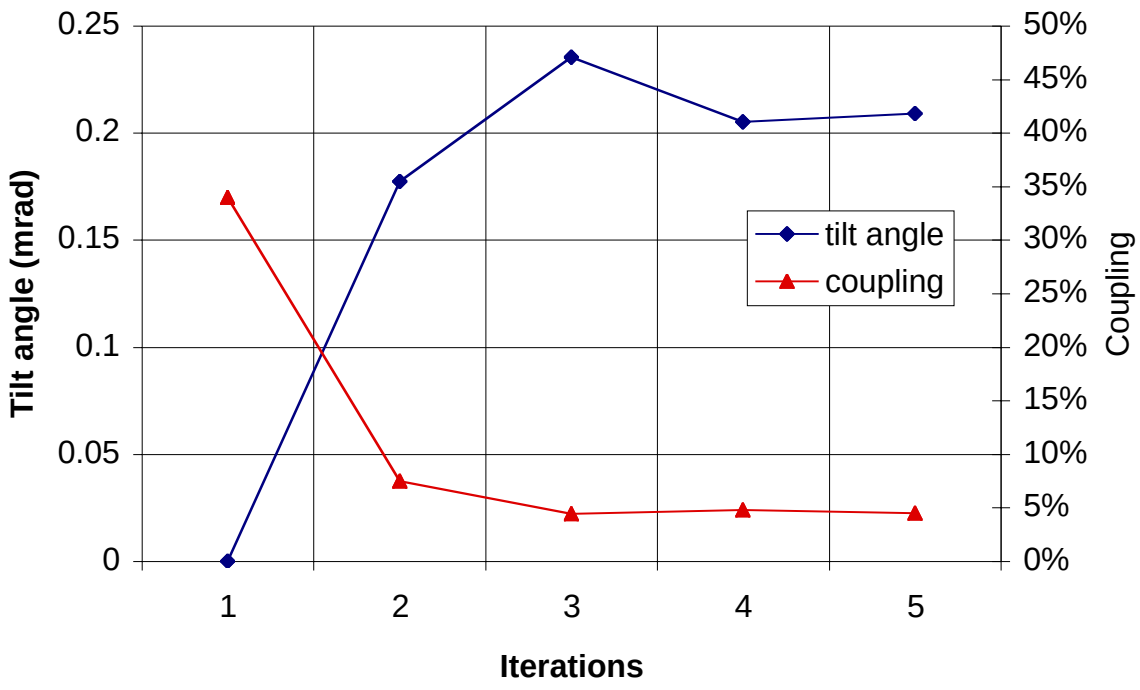
The resulting coupling was measured with a pinhole camera and compared with the model value.



The strong response on the main harmonic appears clearly on the result. However a large scaling (factor 1/3) must be applied to the measurement results to match the predicted values. This was explained recently by a calibration problem on beam size measurements.

Coupling correction

This harmonic method could then be used to correct the natural coupling of the machine.



- The iteration was stopped when the amplitude of the motion was comparable to the girder positioning error.
- The correction significantly reduces the coupling

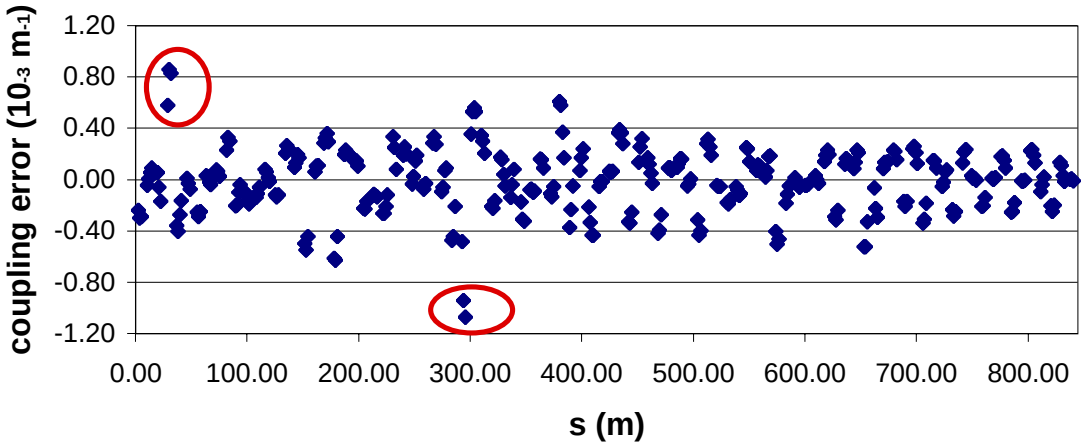
  35 % → 4.5 %

- Using on top the usual magnetic correctors, the coupling value is reduced to 1.7 %. However this is still higher than the normal tuning of 0.7 %.
- The peak angle of 0.2 mrad is too large to be attributed to alignment errors.

Vertical sextupole displacement

Another approach for coupling correction is to use the vertical response of the beam to horizontal kicks: the orbit distortion should be purely horizontal, and any vertical distortion results from coupling errors.

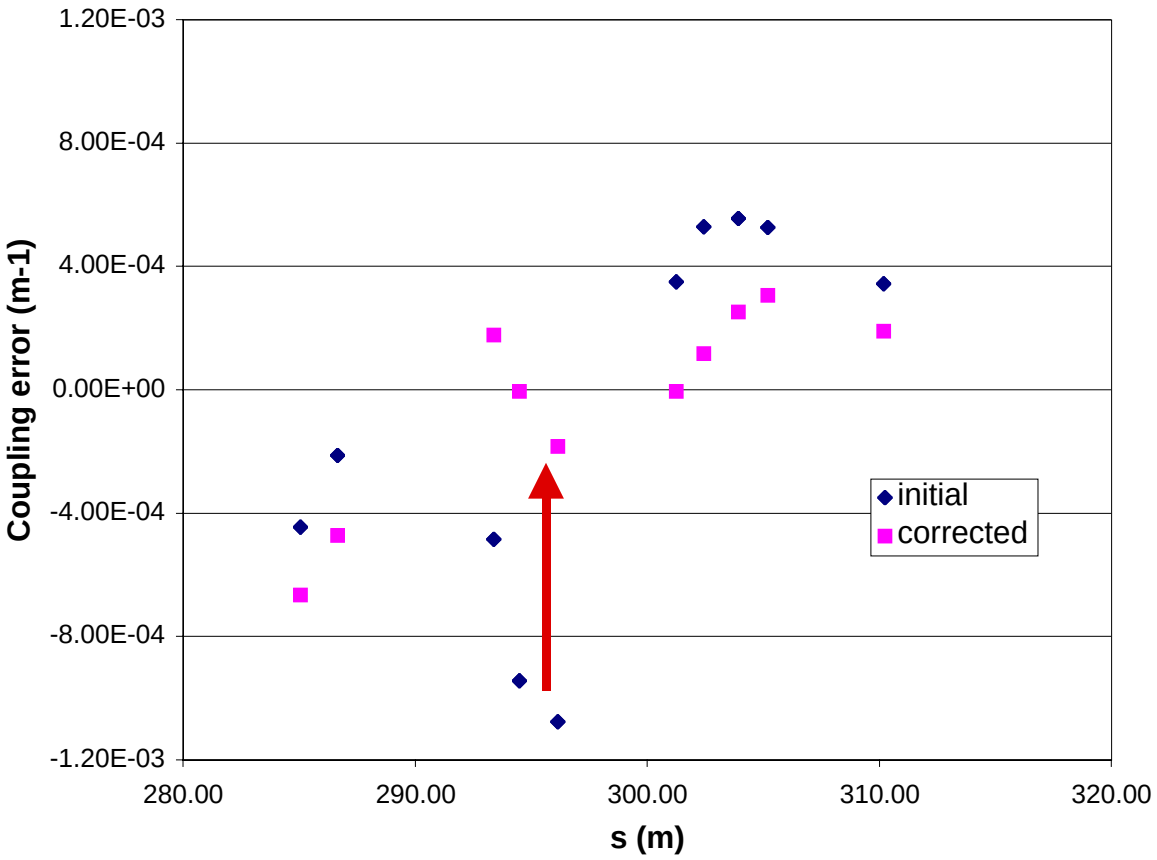
The analysis of the response matrix obtained from measuring the orbit distortion generated by all magnetic steerers gives a model of coupling errors along the circumference.



This modelling shows two particularly bad areas. A local correction of these two points was tried.

- Girder tilt: too large value
- Quadrupole tilt: avoided because of the rigid connection between quadrupole and vacuum chamber
- Sextupole vertical displacement: successfully tested

After moving the sextupoles (~0.5 mm motion), a new measurement allows comparing the errors before and after correction:



The coupling is also reduced:

	natural	corrected
Initial	12 %	0.8 %
After	8 %	0.6 %

Conclusions

We are now confident that there is in all cases a good agreement between the modelling and the experiments.

Vertical orbit correction

The correction works as expected, the machine can run without magnetic steerers and the girder positions are not in contradiction with the survey. Nevertheless, the final performance of the machine is not improved

⇒ This remains a test

Coupling / girder tilts

Again the correction is efficient, but the machine performance is not improved. In addition

- The tilts have a strong side effect on horizontal position
- The final position are by far too large to be acceptable

⇒ This cannot be implemented

Coupling / sextupole displacement

The resulting position has been kept for normal operation.