Mechanically Induced Influences on the ESRF SR Beam

D. Martin, L. Farvacque
ESRF, Grenoble BP220 38043, France

1. INTRODUCTION

We have conducted a number of experiments over the past year on the influence of mechanical motions on the ESRF SR Beam. High precision jacks installed under the SR quadrupole girders are used to make movements while beam (typically 5 mA) is in the machine. These movements are controlled by the HLS. All interesting beam parameters are measured before and after movements are made. Two families of beam effects have been looked at. The closed orbit is examined by pure vertical translation while the influence on the coupling is studied by introducing tilts on the girders. Although all of our experiments have been made in the vertical plane, the results can be equally applied in the horizontal plane. The results of our efforts to date are presented here.

2. JACK MOVEMENTS AND THE CONTROL OF JACK MOVEMENTS

Figure 1 shows the position of the HLS and Jacks on the G10, G20 and G30 girders. A schematic of the typical ESRF cell is shown in figure 2. Longitudinal tilt motion is a rotation about the middle jack on a girder in the sense of the travel of the beam. Radial tilt motion is about the center of the girder in the sense perpendicular to the beam travel. Vertical movements are made on the G10, G20 and G30 girders.

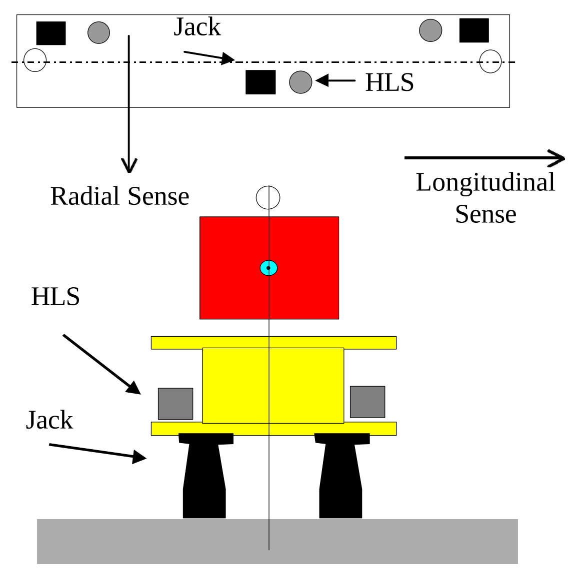

Fig. 1 Position of the HLS and Jacks on a typical SR G10, G20 and G30 girder

Jack movements are calculated from longitudinal and radial tilt values issued from calculations of beam parameters. These tilt values are translated into movements for the three jacks under each girder. Corresponding expected HLS readings at the jack positions are also calculated and used as a control for these movements. The difference between the jack movement and the expected HLS reading is the precision of the movement.

$$Movement\ Error = M_{hls} - M_{jack}$$

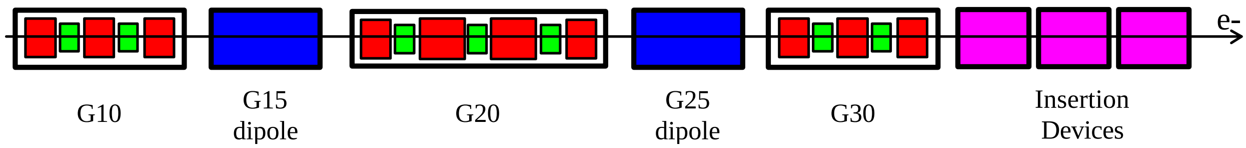

Fig. 2 Typical ESRF Cell

In reality, it is not quite as simple as this. When the jacks are moved, water moves around the pipe system creating a wave. To calculate the real precision of a jack movement this wave must be modeled out. Two methods are used. The first is a Fourier Series:

$$y(x) = \frac{1}{2}a_0 + \sum_{k=1}^{L-1}\left(a_k \cos\left(\frac{\pi}{L}kx\right) + b_k \sin\left(\frac{\pi}{L}kx\right)\right) + \frac{1}{2}a_L \cos \pi x$$

where

$$a_k = \frac{1}{L}\sum_{x=0}^{2L-1} y(x)\cos\left(\frac{\pi}{L}kx\right), \qquad \text{k=0,1,…,L}$$

$$b_k = \frac{1}{L}\sum_{x=0}^{2L-1} y(x)\sin\left(\frac{\pi}{L}kx\right), \qquad \text{k=1,2,…,L-1}$$

The Fourier series is not always appropriate. Blockages in the HLS water system and jacks that do not move as expected create discontinuities. In this case a cubic spline model is used. This is given by:

$$\begin{bmatrix}
a_1 & b_1 & c_1 & & & & & & & \\
b_1 & a_2 & b_2 & c_2 & & & & & & \\
c_1 & b_2 & a_3 & b_3 & c_3 & & & & & \\
 & . & . & . & . & . & & & & \\
 & & . & . & . & . & . & & & \\
 & & & . & . & . & . & . & & \\
 & & & & . & . & . & . & . & \\
 & & & & & c_{n-6} & b_{n-5} & a_{n-4} & b_{n-4} & c_{n-4} \\
 & & & & & & c_{n-5} & b_{n-4} & a_{n-3} & b_{n-3} \\
 & & & & & & & c_{n-4} & b_{n-3} & a_{n-2}
\end{bmatrix}
\begin{bmatrix} u_2 \\ u_3 \\ u_4 \\ . \\ . \\ . \\ . \\ u_{n-3} \\ u_{n-2} \\ u_{n-1} \end{bmatrix}
=.
\begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ . \\ . \\ . \\ . \\ d_{n-4} \\ d_{n-3} \\ d_{n-2} \end{bmatrix}$$

where

$u_2, u_3, \ldots, u_{n-1}$ are the model z values

and

$$a_i = \frac{2}{3} + 6\rho \;,\quad b_i = \frac{1}{6} - 4\rho \;,\quad c_i = \rho \;,\; d_i = z_{i+2} - 2z_{i+1} + z_i$$

and

$z_1, z_2, \ldots z_{i+1}$ are the HLS readings and $\rho = 100$ is the weight.

An example of a jack movement is given in figure 3.

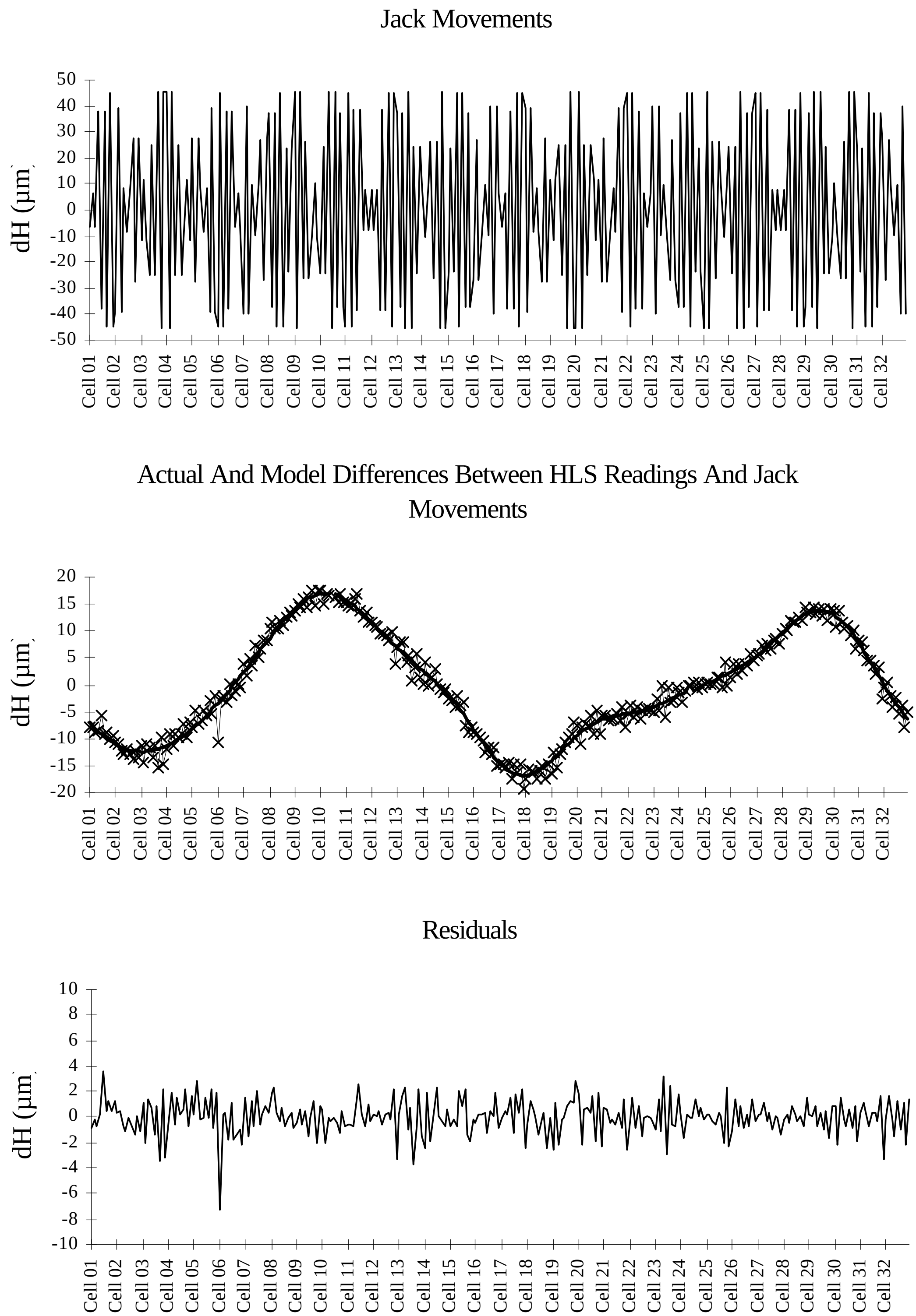

Fig. 3 Sequence showing jack movements, the actual and modeled difference between HLS readings and jack movements and the residuals between the actual and modeled values.

The residual standard deviation of 1.3 µm represents both the precision of the 288 jack movements and the natural evolution in time of the Storage Ring girders.

3. VERTICAL BEAM CLOSED ORBIT

3.1 The Effect on the Closed Orbit by One Girder Movement

Eighteen jacks were moved independently by 10 µm. The motion was checked by deducing the displacement from the beam position readings all around the Storage Ring. There is an agreement of better than 1 µm between the jack movement, the HLS and the beam. It was also determined that deterioration in the standard deviation of 1 µm in the vertical alignment corresponds roughly to a deterioration of 80 µm in the horizontal closed orbit.

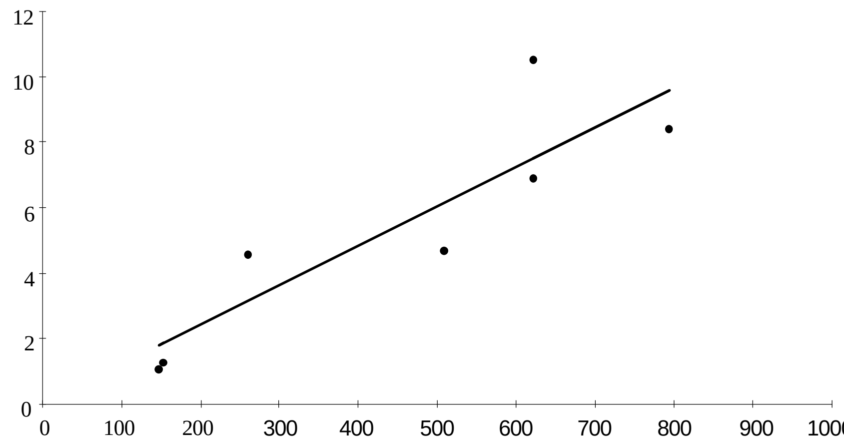

Fig. 3 Deterioration of the horizontal closed orbit as function of deterioration of the vertical alignment

3.2 Complete Correction of the Closed Orbit Using Girder Movements

The response matrix of the vertical closed orbit to girder motion was computed for the theoretical machine. In simulation analysis, it was confirmed that pure rotation of girders was more efficient than pure translation. It was therefore decided to correct the machine using only girder rotations. The response matrix therefore relates the 96 girder rotations to the 224 BPM vertical position measurements:

$$\begin{pmatrix} z_1 \\ \vdots \\ z_m \end{pmatrix} = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix} \cdot \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_n \end{pmatrix}$$

with $m = 224$, and $n = 96$, or

$$\mathbf{Z} = \mathbf{R} \cdot \Theta$$

The solution for minimizing the measured vertical orbit is obtained by solving this over-determined system. This is done by the Singular Value Decomposition method. The system matrix **R** can be expressed as:

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

V is a basis of normalized orthogonal correction vectors (“Eigen corrections”),

U is the corresponding set of normalized orthogonal orbits (“Eigen orbits”),

The diagonal matrix **S** indicates the "amplification" of the machine (in m/rad) for each

Eigen correction vector:

$$z_{k\,rms} = S_k \sqrt{m/n}\, q_{k\,rms}$$

The least square solution of the system is obtained by:

$$\Theta = \mathbf{V} \cdot \mathbf{S}^{-1} \cdot \mathbf{U}^{\mathrm{T}} \cdot (-\mathbf{Z})$$

By restricting the diagonal **S** matrix to the largest Eigen values, it is possible to tune the correction and keep only the most efficient correction vectors. Simulations indicated that least efficient vectors (above the 37th vector) could induce very large displacements. In consequence they were not used in the correction. As the same method is applied for the normal orbit correction using magnetic steerers, the correction procedure was set as:

- Start from a perfectly corrected machine.
- Reduce the number of steerer correction vectors so that the vertical orbit blows up significantly (z_{rms} < 300 μm).
- Measure the vertical closed orbit and compute the mechanical correction with 36 vectors
- Apply the mechanical correction

Table 1 Main Parameters for Alignment Test

No. Vectors	Orbit Standard Error Before Movements (μm)	Orbit Standard Error After Movements (μm)	Movement Standard Error (μrad)	Maximum Motion (μrad)	Standard Deviation Of Steerers (mA)
32	269	191	21	48	76
12	302	194	18	25	33
6	329	217	10	30	25
5	340	220	6	16	22
3	493	215	6	18	21

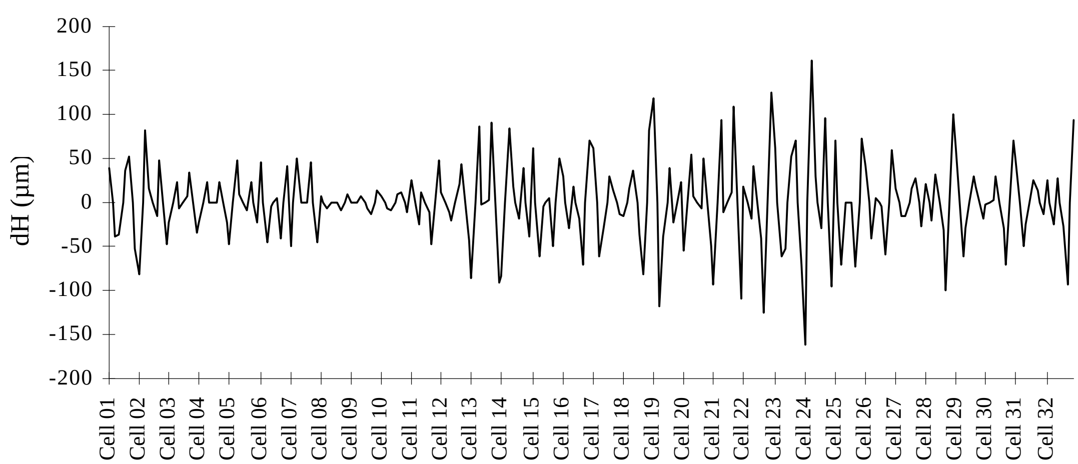

Fig. 4 Final machine position after alignment experiment.

Table 1 shows the results of this test. Five iterations were made for an overall reduction factor of 3.5 in the steerer strength. The standard deviation in the change of machine alignment is 51 µm. The final position of the machine is shown in figure 4.

At the final stage, we were left with 3 Eigen vectors powered on the steerers. As they are the most efficient, their cancellation needed some care that we could not take because of lack of time. However it should raise no problem. On the other hand, the relatively large residual orbit value of 215 µm was due to the choice of a limited number of correction vectors (36) to avoid very large movements. The residual orbit has then to be corrected with the steerers.

4. BEAM COUPLING

The horizontal/vertical betatron coupling is responsible for the major part of the vertical emittance of the Storage Ring. It is defined as the ratio *k* of the vertical to the horizontal beam emittances:

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

In a perfect machine coupling does not exist. It is a result of magnet imperfections and alignment tilt errors. Since the brilliance is inversely proportional to the coupling, its reduction is a way of optimizing the performance. This is usually done by powering skew quadrupole correctors. Alternatively, coupling can be varied by tilting girders in the radial direction.

4.1 Calibration of a Harmonic Tilt

The coupling is mainly sensitive to the excitation of the resonance close to the betatron tune difference ($\nu_x - \nu_z = 25$ in the case of the 4 nm lattice). So a systematic transverse tilt was applied to the girders on a corrected machine, according to this 25th harmonic. The average value $\bar{\varphi} = \left\langle \frac{\varphi_x - \varphi_z}{\nu_x - \nu_z} \right\rangle$ over the quadrupoles of each girder is used to generate a tilt angle $\theta = \hat{\theta}\cos(25\bar{\varphi})$. The value of the peak angle was varied between 0 and 1 mrad. For comparison, the same tilt was applied to 2 different lattices: it corresponds to the maximum response of the 4 nm lattice and should have almost no effect on the low β_z lattice. Resulting coupling values are shown in table 2

The evolution with correction on can be compared with the model, as shown of figure 5 for the 4 nm lattice and on figure 6 for the low β_z lattice. The strong effect of harmonic 25 on the 4 nm machine clearly appears, while the low β_z machine is insensitive (small fluctuations may be linked to unavoidable small differences in horizontal orbit). The large deviation (factor 2 to 3) compared to the model is not understood at present.

Table 2 Coupling values as a function of radial tilt angle

Tilt (mrad)	operation natural	operation corrected	low b_z natural	low b_z corrected
0	0.5	7.1	2.3	25
0.2	4.5	4.4	2.2	23
0.4	11.5	17.3	2.3	27
0.6	54	33	2.0	27
0.8	97	105	1.9	2.4
1.0	112	130	1.9	33

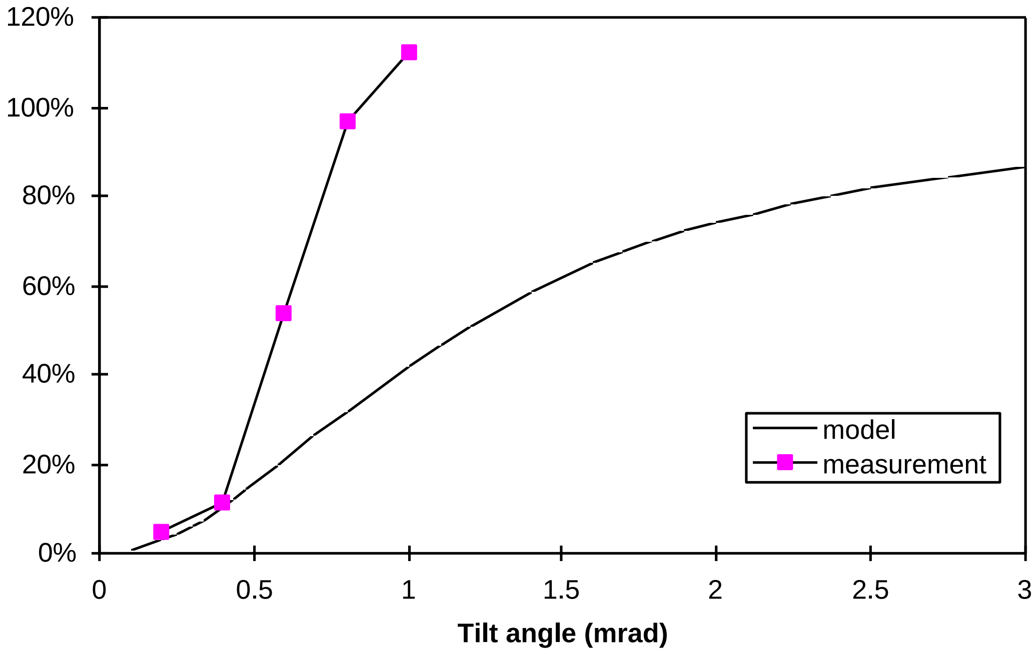

Fig. 5 Coupling on 4 nm lattice

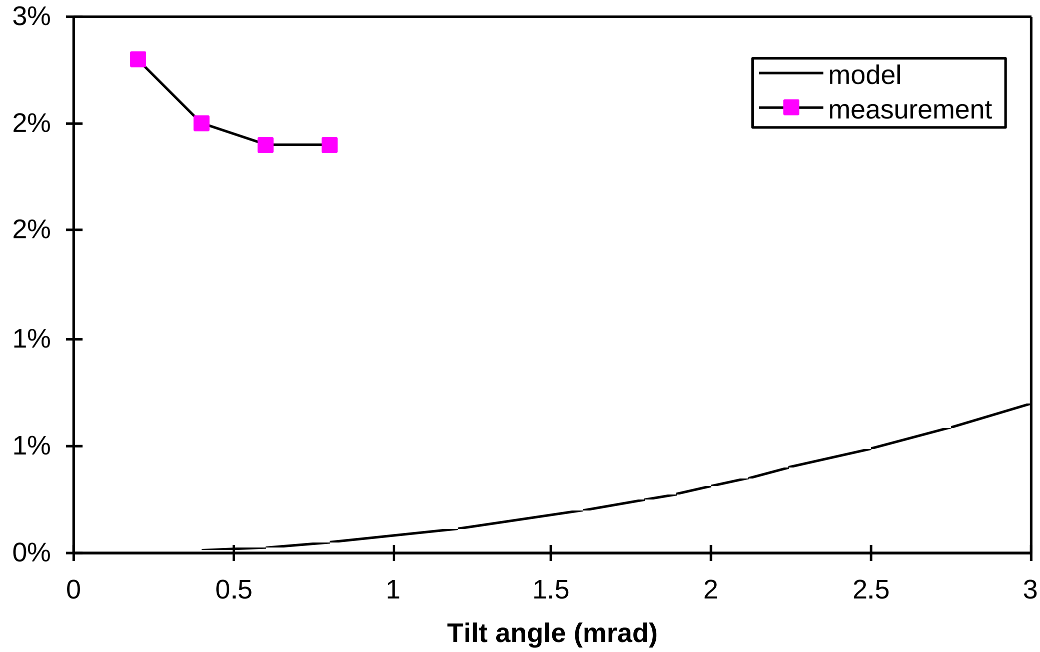

Fig. 6 Coupling on low b_z lattice

4.2 Correction of Harmonic 22 With the SR Girders

The same method as in the previous experiment was applied here on the low b_z lattice, correcting the resonance ν_x - ν_z = 22 by driving the girder tilts with a linear combination of 2 orthogonal settings providing the full flexibility of tuning. A tilt amplitude of 1 corresponds to a sinusoidal distribution of tilt angles with 0.5 mrad peak amplitude (or 0.353 mrad rms.). The 1st step is derived from the settings of the standard magnetic correction. Next steps are computed by minimizing the beam spot with the magnetic correctors and estimating an equivalent step on girder tilts.

Table 3

Angle (mrad rms.)	Phase (°)	C1	C2	Coupling
0	0	0	0	34 %
0.1768	12.65	0.49	0.11	7.5%
0.2358	13	0.65	0.15	4.4 %
0.2051	23.5	0.533	0.232	4.8 %
0.2093	19	0.560	.193	4.5 %

The iteration was stopped when the amplitude of the last step was of the order of the girder positioning error (a few microns rms.). At the stage, the difference resonance looked perfectly corrected. The equivalence between girder tilt amplitude and magnetic correction amplitude is experimentally determined as:

1 A is equivalent to -0.56 mrad (rms.)

Vertical motion of the girder jacks was successfully used to correct one resonance. As a consequence, the natural coupling of the low β_z lattice was reduced from 30% down to 4.5%. The correction was then continued by correcting the 2nd resonance ($\nu_x + \nu_z = 51$) and refining the correction with magnetic correctors:

Table 4

resonance	Amplitude (A)	Phase (°)
$\nu_x - \nu_z = 22$	0.0819	43.4
$\nu_x + \nu_z = 51$	0.7245	-133.4

The residual coupling was then 1.7 %, still higher than the normal tuning of 0.7 %. Reducing this value further done following the standard procedure needed a measurement and analysis of the coupled response matrix of the machine. This was not tested. The mechanical correction alone was not expected to give a better result, since the same harmonic correction is performed by the magnet correctors. However the large number of girders used in the process induces less excitation of other harmonics than the 16 correctors. It should also give more freedom for additional corrections.

The tilt rms. value of 0.21 mrad introduced in the machine is very large. It cannot represent the compensation a residual harmonic component with such amplitude in the girder alignment. It probably compensates another coupling source (individual positioning of magnets, magnetic tilt angle,…).

5. CONCLUSION

Several experiments have been made using high precision jacks installed under the SR girders relating mechanical motion to vertical closed orbit and coupling.

- the calibration of the movement of one girder,
- the complete correction of the machine by movements made to imitate the action of the steerers,
- the calibration of a harmonic excitation of a coupling resonance as a function of girder tilts,
- the compensation of the principal coupling resonance.

All of these experiments relate exclusively to the vertical plane of the machine. Nevertheless, they can equally be applied in the horizontal. It has been shown that mechanical movements can be used to imitate other correction mechanisms such as the steerers and dramatically improve the functioning of the machine. For both the closed orbit and the coupling, the main interest is to correct residual errors by girder motions so that the starting point for classical guidance techniques can be more finely tuned. In the case of the complete correction of the machine vertical closed orbit one can imagine increasing the resolution of the steerers at the expense of their strength. In the case of the coupling, the girder tilt motions are so large as to render the method unusable. It is not understood why this is the case at present.

Finally, these experiments have provided a chance for the surveyor and the physicist to work more closely and gain a better understanding of each other's priorities and view of the machine. Nevertheless, a word of caution must be expressed. We have had the opportunity to perform these experiments on a machine where all parameters are well known. Clearly, in order to perform beam-based alignment one must first have an well-understood and behaved beam.

6. REFERENCES

[1] L. Farvacque, *Test of Machine Realignment*, Machine Technical Note, 36-96/MDT, ESRF, France. 11 July 1996.

[2] L. Farvacque, D. Martin, *Coupling Correction Using the Girder Tilts*, Machine Technical Note, 55-96/MDT, ESRF, France. 1 October, 1996.

[3] D. Martin, *Control of Jack Movements with Beam and HLS Readings*, Machine Technical Note, 20-97/MDT, ESRF, France. 11 April 1997.

[4] G. Gatta, *Modelisation De Phenomenes Cycliques Et Re-Etalonage De Capteurs Capacitifs*, Stage Professional I.U.P. 2 Mathematiques Appliquees et Industrielles, ESRF, France, August 1997.