ACTION AND PHASE JUMP ANALYSIS FOR LHC ORBITS*

O.R. Blanco†, J.F. Cardona‡
Physics Department – Universidad Nacional de Colombia, Bogota, Colombia

Abstract

Action and phase orbit analysis is implemented to detect magnetic errors in LHC orbits of late 2009 run. The last achievements in the theory of action and phase jump analysis have been included to reduce action and phase plots noise and to increase precision on the calculation of linear errors. The validation of the implementation is performed by MAD-X simulations of the LHC lattice V6.5, where dipole and quadrupole errors are included and recovered within 1.53%. Then, the implementation is applied to experimental orbits, taken from the 2009 run during November and December, where several interaction regions are analyzed.

THE ACTION AND PHASE METHOD

The Method Briefly

When a magnetic error θ_z is present at some particular point $s = s_\theta$, it was shown in [1] that the trajectory of the particle can be described independently before and after the error:

- Before the error ($s < s_\theta$)

$$z(s) = \sqrt{2J_0\beta_z(s)}\sin(\psi_z(s) - \delta_0) \tag{1}$$

- After the error ($s > s_\theta$)

$$z(s) = \sqrt{2J_1\beta_z(s)}\sin(\psi_z(s) - \delta_1) \tag{2}$$

where J_0 and δ_0 are the action and phase before de error while J_1 and δ_1 correspond to the action and phase after the error. Here z represents either the x, or the y plane. With these equations, using the Courant–Snyder parameters to propagate the particle trajectory through the error and after some algebra and trigonometric identities we obtain the magnetic error as:

$$|\theta_z| = \sqrt{\frac{2J_1 + 2J_0 - 4\sqrt{J_1J_0}\cos(\delta_1 - \delta_0)}{\beta(s_\theta)}} \tag{3}$$

* Work supported by **Departamento Administrativo de Ciencia, Tecnologia e Innovacion (COLCIENCIAS), Programa Jovenes Investigadores e Innovadores "Virginia Gutierrez de Pineda" 2009** and **Direccion de Investigacion Sede Bogota, Universidad Nacional de Colombia (DIB, UNAL)**

† orblancog@bt.unal.edu.co
‡ jfcardona@unal.edu.co

The magnetic error θ_z could be generated by any the multiple components in the magnetic field multipole expansion.

$$\begin{aligned}\theta_x =& B_0 - B_1x(s_\theta) + A_1y(s_\theta) + 2A_2x(s_\theta)y(s_\theta)\\ &+ B_2[-x^2(s_\theta) + y^2(s_\theta)] + \cdots \end{aligned}\tag{4}$$

$$\begin{aligned}\theta_y =& A_0 + A_1x(s_\theta) + B_1y(s_\theta) + 2B_2x(s_\theta)y(s_\theta)\\ &+ A_2[x^2(s_\theta) - y^2(s_\theta)] + \cdots \end{aligned}\tag{5}$$

with $A_n = B'la_n/B\rho$ and $B_n = B'lb_n/B\rho$

When a magnetic error is present, there is a noticeable change in the local action and phase of the orbit specially at the interaction regions where usually there are significant changes in the beta functions (see Fig. 2). Magnetic error strength and sign is recovered directly from the calculation and magnetic errors are calculated by linear o power regressions according to [2], [3], [4].

For **dipolar errors**, no dependence with any of the transverse coordinates is expected.

$$B_0 = \theta_z \tag{6}$$

For **quadrupolar errors**, linear dependency with the transverse coordinates is expected.

$$A_1 = \frac{\theta_x y(s_\theta) + \theta_y x(s_\theta)}{x^2(s_\theta) + y^2(s_\theta)} \tag{7}$$

$$B_1 = \frac{\theta_y y(s_\theta) - \theta_x x(s_\theta)}{x^2(s_\theta) + y^2(s_\theta)} \tag{8}$$

For **sextupolar errors**, quadratic dependency with the transverse coordinates is expected and multiple orbits might be needed.

Requirements

The action and phase method is performed along the coordinate s of the accelerator to obtain (J_i, δ_i), segment by segment, on each i^{th} segment. It means, it requires:

- BPMs readings: Two before the error (to calculate (J_0, δ_0)), two after the error (to calculate (J_1, δ_1))
- The lattice model: To obtain the Courant–Snyder parameters of the accelerator
- Multiturn trajectories: To increase the precision in the polynomial fitting (quadrupolar and sextupolar errors mainly), it is better if the multiturn trajectory is made with high amplitude oscillations

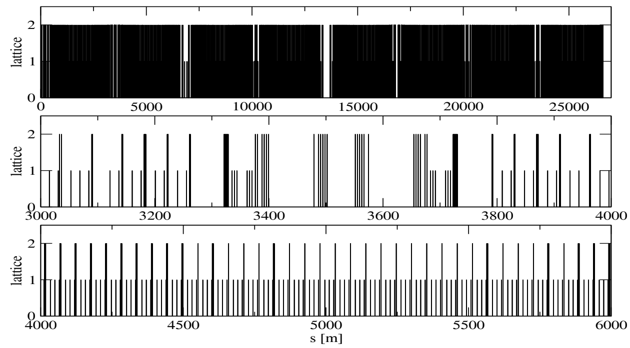

Figure 1: Lattice. (top) The entire lattice, (middle) Zoom in over an interaction region, (bottom) Zoom in over an arc. The 1's represent dipoles and 2's represent quadrupoles.

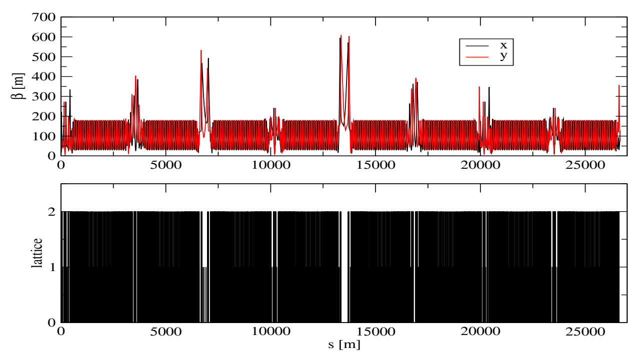

Figure 2: β functions. The higher values are localized over the interaction regions.

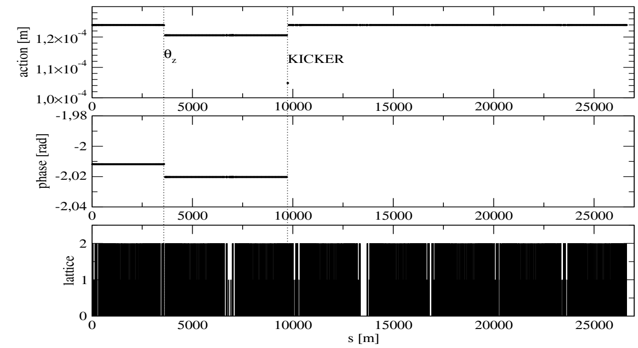

Figure 3: A magnetic error θ_z is located in the lattice and a orbit corrector is used to produce orbits with different amplitudes.

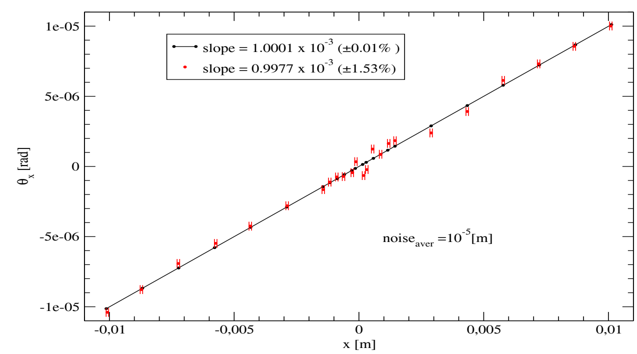

Figure 4: Plot used to calculate the quadratic magnetic error. Precision is decreased when random noise is included in the orbits.

THE LHC IN SIMULATIONS

The LHC lattice model version 6.5 for MAD-X 4.01 was used during the simulations. Figure 1 shows schematically the appearance of the entire lattice, an interaction region and an arc. Lattice functions and beam trajectory position at each BPM are read from output files of the MAD-X simulations

Error Simulations

Dipolar and quadrupolar errors were included in the accelerator.

Orbits with the errors were obtained by MAD-X simulations with the following parameters: Experiments off, period lhcb1, Lattice model V6.5, Energy 450[GeV] (injection), Particle PROTON

A orbit corrector was used to generate orbits with different amplitudes for different simulations.

Calculations were made along the entire s coordinate, BPM by BPM, using custom scripts written in different languages: C, **C++**, **BASH**, PERL, **Python V2.5**.

Figure 3 shows the action and phase jump at the error s_θ calculated from the simulated orbit. In figure 4, a quadrupolar magnetic error of K1=1×10^{-3} was included and recovered at s_θ, showing that the magnetic error precision decreases from $\pm0.01\%$ to $\pm1.53\%$ when random noise between $1\sim10\%$, similar to the experimental data is included in the simulations. Simulations were done with sextupoles off but we know they introduced additional noise in the third significant figure which can be neglected when compared with the experimental noise.

THE LHC EXPERIMENTAL ORBITS

The Data

Data taken from the 2009 LHC run during November and December was processed. It consisted of beam transverse positions of one bunch in multiple turns in sdds format. After applying the method, high noise appears in the action and phase plot.

Several techniques were used to reduce the influence of the noise, but best results were obtained with **phase range selection**. From a large number of turns corresponding to one orbit file, only turns in phase[1] are used to calculate one principal orbit, adding turns with same phase and subtracting turns with phase $\bar{\psi}+\pi$.

The magnetic error must be calculated at a s_θ position where the β functions are high. Figure 5 shows that s_θ

[1] Each turn has a different averaged phase $\bar{\psi}$, but in this case we choose only those that are similar within a range that should be chosen by looking the turns along the fraction of the accelerator that is under analysis.

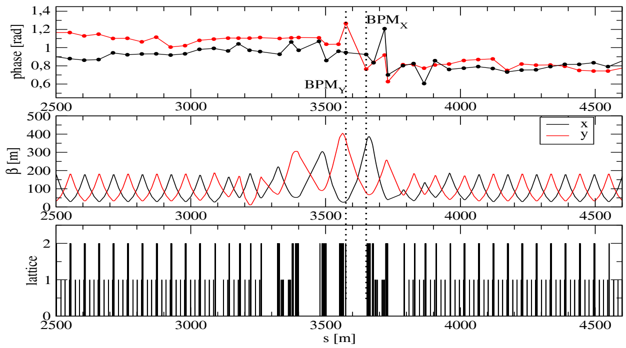

Figure 5: Selection of the s_θ where the error is calculated.

is different for the x and y, coordinates. If both planes are supposed to be analyzed at the same time, for example, looking for skew or coupling error, then s_θ should be a point where none of them is a minimum.

IR3

As an example, figure 6 shows the phase difference before and after the IR3. The result of performing the analysis in this region is shown in figure 7 where a main quadrupole error is detectable, but more data will be needed to determine it more precisely.

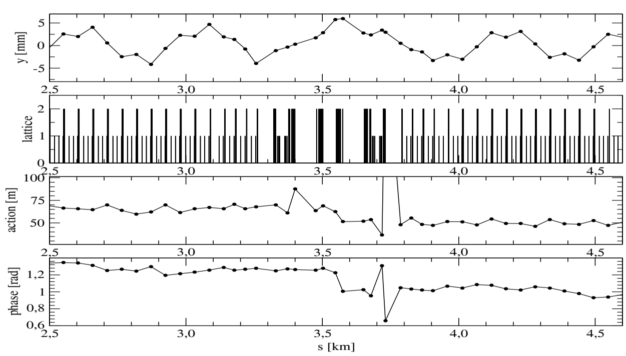

Figure 6: Interaction region 3. A phase jump is observed from data.

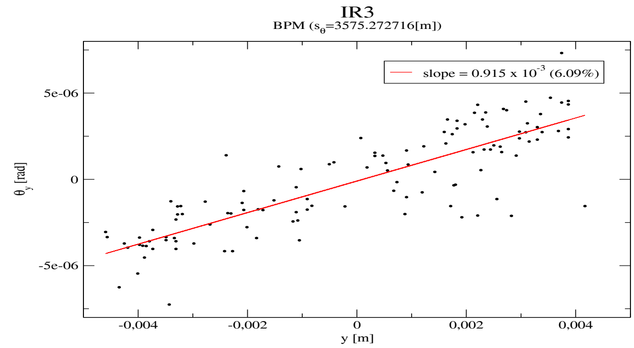

Figure 7: Interaction region 3. A phase jump is observed from data.

CONCLUSIONS

Even though simulations show that possible LHC magnetic errors can be recovered within 1.53% uncertainty, the data shows significant noise in the action and phase plots. In this paper, we have shown a way to reduce this problem through careful selection of turns (phase range selection) and building difference orbits from these selected turns.

ACKNOWLEDGMENTS

The authors want to thank Rogelio Tomás García and his team at CERN for providing the LHC data, interesting discussions and suggestions for the analysis presented here.

REFERENCES

[1] J. Cardona et. al., Linear and non linear magnetic error measurements using action and phase jump analysis. PRST-AB 2009.

[2] J. Cardona, Linear and Non linear studies at RHIC Interaction regions and Optical Design of the Rapid Cycling Medical Synchrotron. PhD Thesis, State University of New York at Stony Brook, 2003.

[3] J. Cardona et. al., Measuring local gradient and skew quadrupole errors in RHIC irs. EPAC 2004.

[4] J. Cardona et. al., Non linear error analysis from orbit measurements in the SPS and RHIC. PAC 2005.

[5] S. Y. Lee, Accelerator Physics. World Scientific, 1999.

[6] H. Wiedermann. Particle Accelerator Physics. Third Edition. Springer, 2007.

[7] J. Cardona, Action and Phase analysis to determine sextupole errors in RHIC and the SPS. PAC 2003.

[8] J. Cardona Local magnetic error estimation using action and phase jump analysis of orbit data. PAC 2007.

[9] F. Schmidt, MAD-X User's guide. `http://mad.web.cern.ch/mad/`

[10] F. Schmidt, A MAD-X primer. `http://mad.web.cern.ch/mad/`

[11] Design reports, beam parameters, lattice and optics from `http://lhc.web.cern.ch/lhc/`