Action and Phase Jump Analysis for LHC Orbits

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Action and phase
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Requirements

The LHC in simulations
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Action and Phase

\[ z(s) = \sqrt{2J_z\beta_z(s)} \sin(\psi_z(s) - \delta_z) \]  

(1)

When a magnetic error \( \theta_z \) is present at \( s = s_\theta \), the trajectory of the particle can be described independently before and after the error:

- **Before the error \( s < s_\theta \)**
  \[ z(s) = \sqrt{2J_0\beta_z(s)} \sin(\psi_z(s) - \delta_0) \]  
  (2)

- **After the error \( s > s_\theta \)**
  \[ z(s) = \sqrt{2J_1\beta_z(s)} \sin(\psi_z(s) - \delta_1) \]  
  (3)

\( J_0 \) and \( \delta_0 \) are the action and phase before the error,
\( J_1 \) and \( \delta_1 \) correspond to the action and phase after the error.
With this equations, using the Courant–Snyder parameters to propagate the particle trajectory through the error (and after some algebra and trigonometric identities...)

We obtain the **KICK magnitude** as

\[
\theta_z = \sqrt{\frac{2J_1 + 2J_0 - 4\sqrt{J_1J_0} \cos(\delta_1 - \delta_0)}{\beta(s_\theta)}}
\]  

(4)
The kick \( \theta_z \) could be generated by any the multiple components in the magnetic field multipole expansion.

\[
\theta_x = B_0 - B_1 x(s_\theta) + A_1 y(s_\theta) + 2A_2 x(s_\theta) y(s_\theta) + B_2 [-x^2(s_\theta) + y^2(s_\theta)] + \cdots \tag{5}
\]

\[
\theta_y = A_0 + A_1 x(s_\theta) + B_1 y(s_\theta) + 2B_2 x(s_\theta) y(s_\theta) + A_2 [x^2(s_\theta) - y^2(s_\theta)] + \cdots \tag{6}
\]

with \( A_n = B' l a_n / B_\rho \) and \( B_n = B' l b_n / B_\rho \)
Linear errors

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

\[ B_0 = \theta_z \quad (7) \]

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

\[
A_1 = \frac{\theta_y y(s_\theta) + \theta_x x(s_\theta)}{x^2(s_\theta) + y^2(s_\theta)} \quad (8)
\]

\[
B_1 = \frac{\theta_y y(s_\theta) - \theta_x x(s_\theta)}{x^2(s_\theta) + y^2(s_\theta)} \quad (9)
\]
Requirements

- BPMs readings
  - Two before the error (to calculate \((J_0, \delta_0)\))
  - Two after the error (to calculate \((J_1, \delta_1)\))
- The lattice model
  - To obtain the Courant–Snyder parameters of the accelerator
- Multiturn runs
  - To increase the precision in the polynomial fitting (quadrupolar and sextupolar errors mainly), it is better if the multiturn run is made with high oscillations
The LHC

Images taken from [1] and [5]
Dipolar and quadrupolar errors were included in the accelerator.

Orbits with the errors were obtained by simulations

- MAD-X V4.01
  - Experiments off
  - Period lhcb1
  - Lattice model V6.5
  - Energy 450[GeV] (injection)
  - Particle PROTON
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Ending
Including noise

\[ \text{slope} = 1.0001 \times 10^{-3} \text{ (±0.01\%)} \]

\[ \text{slope} = 0.9977 \times 10^{-3} \text{ (±1.53\%)} \]

\[ \text{noise}_{\text{aver}} = 10^{-5} \text{[m]} \]

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Phase range selection

Phase average is calculated per orbit, then orbits with similar phase have approximately same behaviour.
Analysing IR3
s coordinate selection
Error

**BPM (s=3575.272716[m])**

- **slope = 0.915 \times 10^{-3} (6.09\%)**
Conclusions

- Simulations show that LHC linear magnetic errors could be recovered within 1.53%.
- Extension to sextupolar error has not been possible with this run.
- Local error in IR3 has been identified.
- Still some noise in the plots from the multiturn data. Noise could be reduced with data from multiple bunches.
- IRs can be analysed independently.
- Phase should be a continuum function (it might affect averages).
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Thank you.
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Coordinate system

The coordinate system is the usual \((x, y, s)\), used for periodic accelerators.
LHC lattice model
LHC lattice model

- LHC lattice model V6.5 (for MAD-X)
  - Monitors (BPMs), to extract simulated orbits
  - Sextupole correctors on arcs are turned off
  - All elements are used to extract $\beta$ and $\psi$ functions
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