Algorithms to estimate corrections in the interaction regions of the LHC using action and phase jump analysis

Javier Cardona

Universidad Nacional de Colombia

Sede Bogotá

One-Turn Beam Trajectory Equations

Conventional

$$y(s) = \sqrt{2J_c\beta_r(s)}\sin(\psi_r(s) - \delta_c),$$

$\beta_r(s)$ and $\psi_r(s)$ "real" lattice functions,

J_c and δ_c are constants.

Action and Phase Jump (APJ)[1]

$$y(s) = \sqrt{2J(s)\beta_n(s)}\sin(\psi_n(s) - \delta(s)),$$

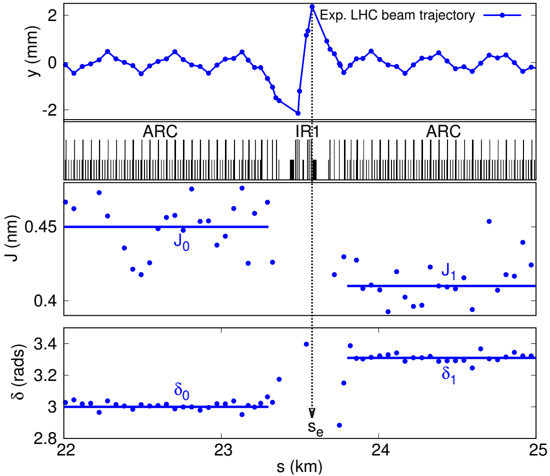
$\beta_n(s)$ and $\psi_n(s)$ nominal lattice functions,

$J(s)$ and $\delta(s)$ jump at error location.

[1] PRSTAB 12, 014002, 2009

Action and Phase Jump Analysis (1)

- If a large number of Beam Position Monitors (BPMs) are available, the APJ equation can be used to make plots of $J(s)$ and $\delta(s)$.
- In the LHC, plots of $J(s)$ and $\delta(s)$ reveal jumps in the IRs.
- These jumps are mainly due to the magnetic errors in the triplet quadrupoles[2].



[2] PRAB 20, 111004, 2017

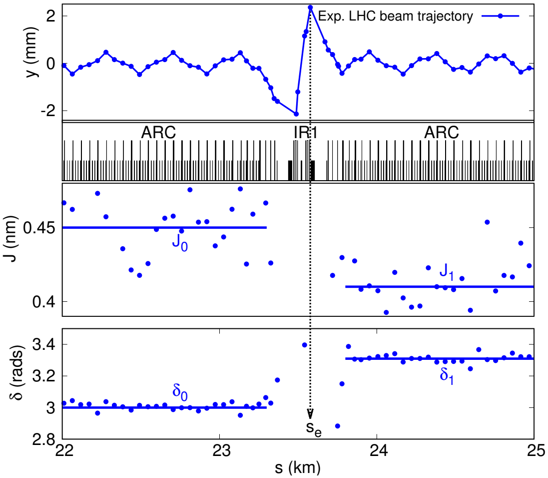
Action and Phase Jump Analysis (2)

- The jumps can be related to magnetic kicks in the left and the right triplets

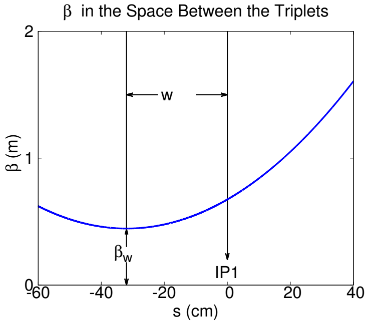
$$|\theta_L| = \sqrt{\frac{2J_0 + 2J_t + 4J_0J_t\cos(\delta_t - \delta_0)}{\beta_n(s_e)}}$$

$$|\theta_R| = \sqrt{\frac{2J_t + 2J_1 + 4J_tJ_1\cos(\delta_1 - \delta_t)}{\beta_n(s_e)}}$$

- J_t and δ_t, the action and phases in the space between the triplets, cannot be extracted from the $J(s)$ and $\delta(s)$ plots.



Action and Phase in the Space between the Triplets



β_{w_r} and w_r are measured in the LHC using the k-modulation technique[3].

$$J_t = J_c \frac{\beta_{w_n}}{\beta_{w\,r}} \cos^2\gamma_c \left(1 + \tan^2\gamma_t\right),$$

$$\delta_t = \psi_n(s_t) + \arctan\left(\frac{L + w_n}{\beta_{w_n}}\right) - \gamma_t,$$

where

$$\gamma_c = \psi_r(s_t) + \arctan\left(\frac{L + w_r}{\beta_{w\,r}}\right) - \delta_c,$$

$$\gamma_t = \arctan\left(\frac{w_n - w_r + \beta_{w\,r}\tan\gamma_c}{\beta_{w_n}}\right).$$

subscript n $->$ nominal variables,
subscript r $->$ real variables.

[3]PRAB 20, 111005, 2017
[4]GetLLM,WEPGW116, IPAC2019

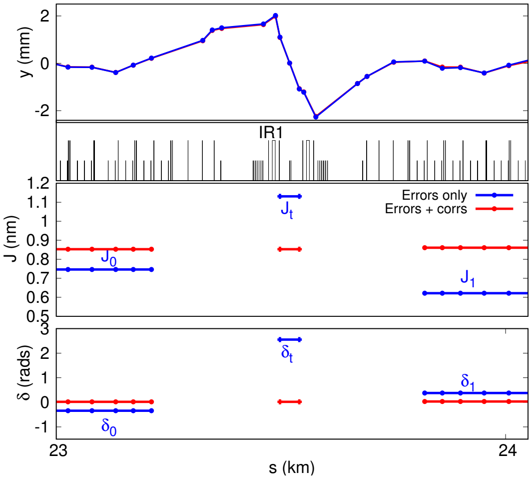
Equivalent Kicks and Corrections

- Once all actions and phases are determined, θ_L and θ_r can be estimated
- θ_L and θ_r can be used to estimate a correction that suppresses the effect of the IR errors such as the AP jump and the β-beating.
- The correction is performed by changing the strength of two quadrupoles per triplet according to the values determined by their corresponding equivalent magnetic kick. Those strength changes correspond to the "corrector strengths".

Example of Correction (APJ plots)

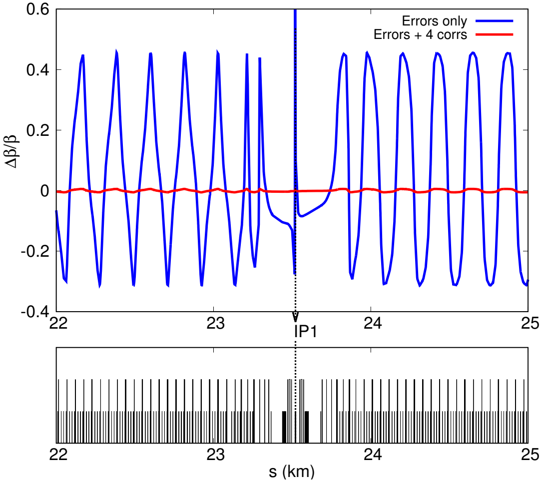
Simulated particle trajectory is generated with the error distribution:

Magnet	Magnetic error ($10^{-5}\ m^{-2}$)	Corr. strengths ($10^{-5}\ m^{-2}$)
Q1L	-0.7	- - - - -
Q2L	0.5	0.58
Q3L	-0.8	0.98
Q1R	0.6	- - - - -
Q2R	1.5	-1.56
Q3R	1	-1.17



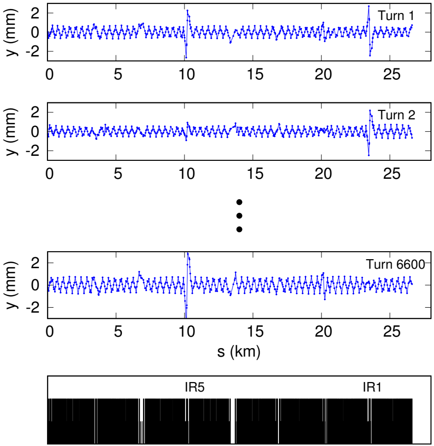
Simulated particle trajectory is generated with the error distribution:

Magnet	Magnetic error (10^{-5} m^{-2})	Corr. strengths (10^{-5} m^{-2})
Q1L	-0.7	- - - - -
Q2L	0.5	0.58
Q3L	-0.8	0.98
Q1R	0.6	- - - - -
Q2R	1.5	-1.56
Q3R	1	-1.17



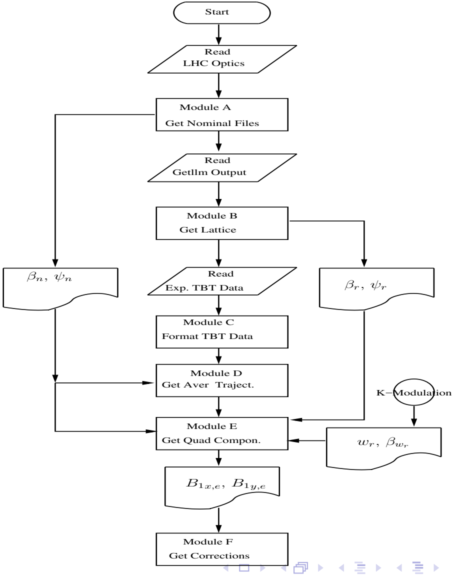
Obtaining the Beam Trajectories

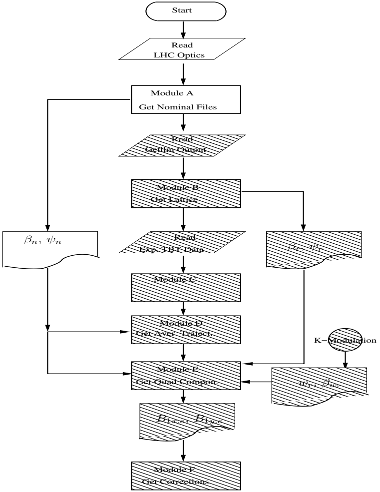
- Beam trajectories are obtained from TBT data.
- In theory, any one-turn trajectory should be sufficient to do APJ analysis. However, noise can be significant in the AP plots.
- Noise can be reduced by selecting turns from the TBT data and averaging them to build a one-turn trajectory known as the "average trajectory".

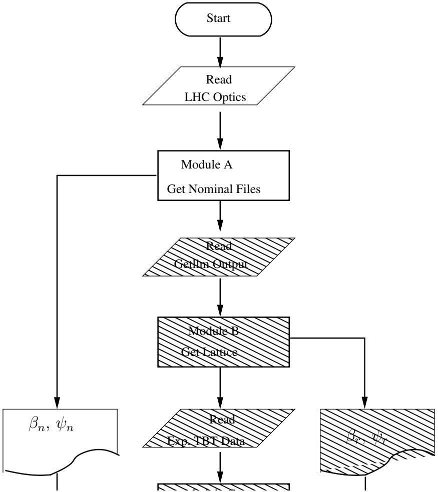


APJ Software

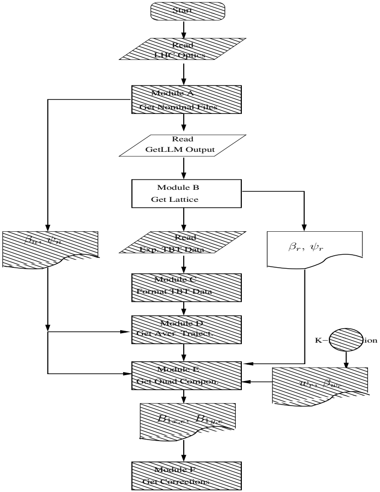
- Lattice Functions
  - Nominal
  - Real
- Average Trajectories
- APJ plots
- Equivalent kicks for the triplets
- Corrections

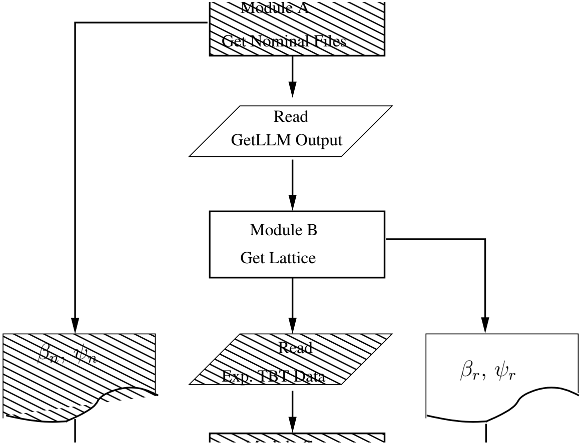



Start
Read LHC Optics
Module A
Get Nominal Files
Read Getllm Output
Module B
Get Lattice
β_n, ψ_n
Read Exp. TBT Data
β_r, ψ_r
Module C
Module D
Get Aver. Traject.
K−Modulation
Module E
Get Quad Compon.
$B_{1x,e}, B_{1y,e}$
Module F
Get Corrections

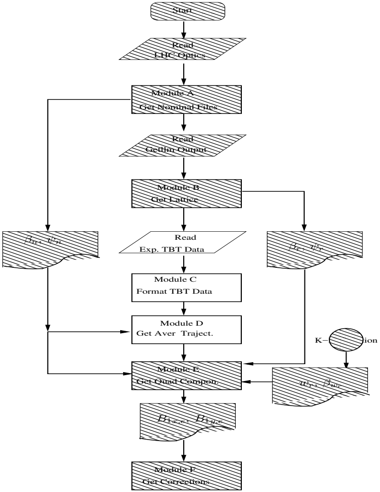

Start
Read
LHC Optics
Module A
Get Nominal Files
Read
Getllm Output
Module B
Get Lattice
β_n, ψ_n
Read
Exp. TBT Data
β_r, ψ_r

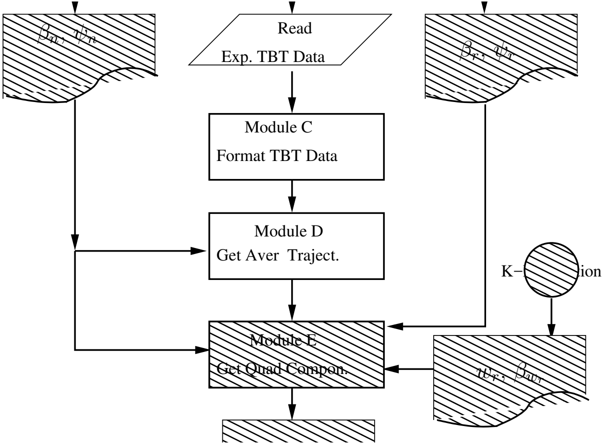
APJ Software (Real Lattice)





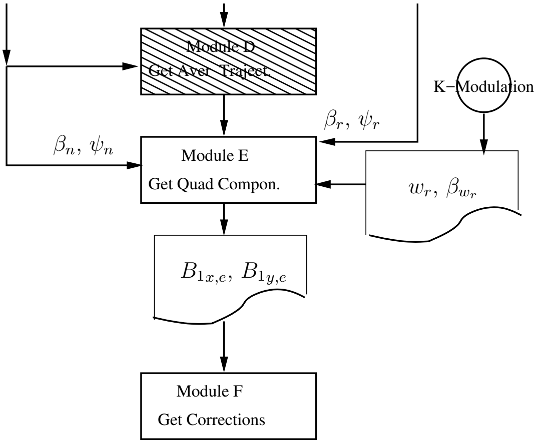
APJ Software (Average Trajectories)





APJ Software (Kicks and Corrections)

- Obtain action and phase plots and estimate averages on each side of the IR (J_o, J_1, δ_0, and δ_1).
- Obtain J_t and δ_t
- Estimate kicks and their quad components ($\theta_{y,e} \sim B_{1y,e}\, y(s_e)$).
- Estimate corrections.



References

- APJ Proof of Principle
  - Javier Cardona and Steve Peggs, Phys. Rev. ST Accel. Beams, vol. 12, p. 014002, Jan. 2009.
- Corrections in LHC Interaction Regions using APJ.
  - Javier Cardona, Carolina García and Rogelio Tomás, Phys. Rev. Accel. Beams, vol. 20, p. 111004, Nov. 2017.
- Estimating J_t and δ_t
  - Javier Cardona, Yohany Rodríguez and Rogelio Tomás, "Introduction of *k*-modulation measurements in APJ analysis to estimate corrections in the interaction regions of the LHC", submitted for publication.
- CERN software
  - Felix Carlier and Rogelio Tomás, Phys. Rev. Accel. Beams, vol. 20, p. 011005, Jan. 2017.
  - Felix Carlier *et al.*, in *Proc. IPAC19*, May 2019, pp. 2773-2776.

ACKNOWLEDGMENTS

- To the students who have used the APJ software in their thesis: **Oscar Blanco, Carolina García, Miguel Morales, Diego Roa, and Yohany Rodríguez**. They have been a great help to test this software in its different stages of development.
- To **Rogelio Tomás García** and all members of the **Orbit Measurement and Correction (OMC)** team at CERN for the support given in the use of their GetLLM and k-modulation software and also for sharing experimental LHC data.