First K-Modulation Measurements in the LHC during Run 2

M. Kuhn[1,2] (maria.kuhn@cern.ch), V. Kain[1], A. Langner[1,2], R. Tomas[1],
[1]CERN, Geneva, Switzerland, [2]University of Hamburg, Germany

Abstract

A fully automatic and online k-modulation measurement system has been developed for the LHC. It takes constraints of various systems such as tune measurement precision and powering limits of the LHC superconducting circuits into account. K-modulation with sinusoidal excitation will also be possible. The first k-modulation and β* measurement results in the LHC in 2015 are presented. In addition, the measured beta functions will be compared to results from the turn-by-turn phase advance method.

Introduction

K-modulation:

- Measure β at locations of individually powered quadrupoles in the LHC.
- Alternative for locations with a non-optimum phase advance between BPMs.
- Applicable to measure β* at interaction points or for BPM offset determination.
- Also used in the LHC to obtain β at the transverse profile monitors in point 4.

Method:

- Quadrupole strength change Δk results in tune change ΔQ.
- Average beta function β along magnet length l:

$$\beta = \frac{2}{l\,\Delta k}\left[\cot(2\pi Q) - \frac{\cos(2\pi(Q+\Delta Q))}{\sin(2\pi Q)}\right] \approx \frac{4\pi\Delta Q}{l\Delta k}$$

K-Modulation in the LHC

- **Superconducting quadrupoles in the LHC.**
- No negative voltage can be applied at the unipolar power converters.
- Upper limits of modulation amplitude ΔI and frequency f: with voltage ΔU, impedance Z, resistance R, inductance L

$$\Delta I = \frac{\Delta U}{Z} = \frac{IR}{2\pi f L}$$

- Example MQY.5R4.B1: $\Delta I_{max} = 26\,A$ at $I = 3\,A, f = 0.1\,Hz$

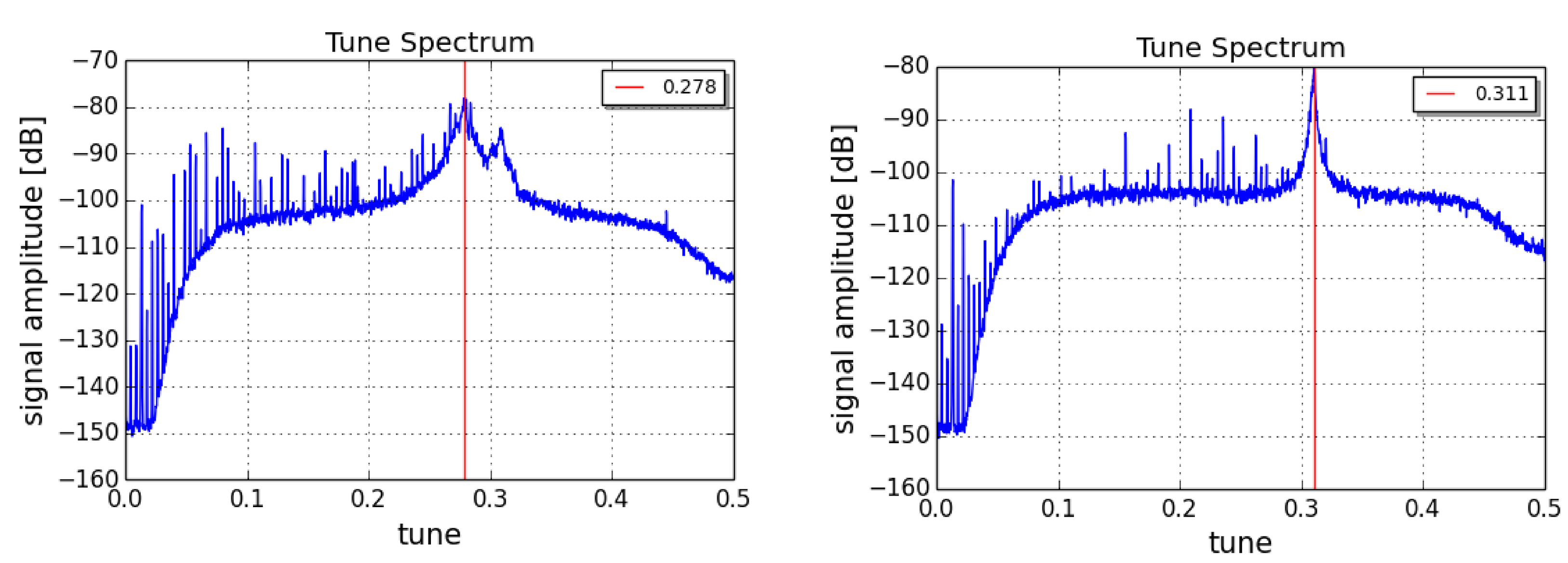
Automatic k-modulation for LHC run 2:

- **Sinusoidal excitation** and k-modulation in steps.

Limitations

- Precision of the β measurement with k-modulation in the LHC is limited by tune noise (typical β measurement error in 2012 is about 10 %).

  ➔Tune noise level ~ 10^{-3} !
- Multiples of 50 Hz lines in the tune spectrum mistaken for tune peak.
- Requires large k-modulation steps, in the order of $\Delta Q \sim 10^{-2}$.
- Maximum possible tune change limited by third order tune resonances in the LHC $\Delta Q \leq \pm 0.015$ at nominal injection tunes $Q_x = 64.28$ and $Q_y = 59.31$.
- **Run 2: extensive progress on the LHC tune acquisition and filtering tool!**



Tune spectrum with dominant 50 Hz lines (left) at injection tunes of nominal 0.28, and with clearer tune peak (right) at collision tunes of nominal 0.31.

- K-modulation not possible during the energy ramp and the β* squeeze.
- Only with low intensity beams.
- Parasitic measurements with physics beam excluded.

Effects of hysteresis for sinusoidal excitation:

Accuracy of quadrupole strength change Δk:

- Error on the measured transfer function ~ 0.1 %.
- Transfer function error from hysteresis is about 0.2 % or smaller.
- Hysteresis alone results in β uncertainty in the order of 10^{-4}.

➔ Negligible small!

Effects of tune decay at 450 GeV:

- Tune decays with time at LHC injection plateau.
- Effect has to be removed assuming linear decay during k-modulation.

Measurement Resolution

Comparison of step and sine modulation results:

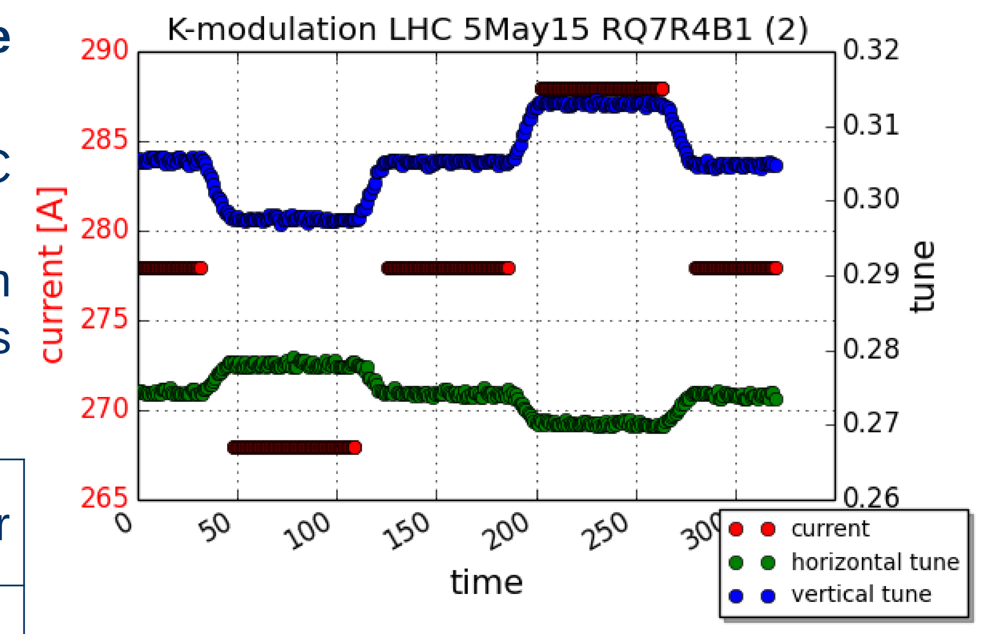
- β fct. measurements in LHC point 4 in 2015.
- Step and sine modulation with identical amplitudes and periods at same quadrupoles.

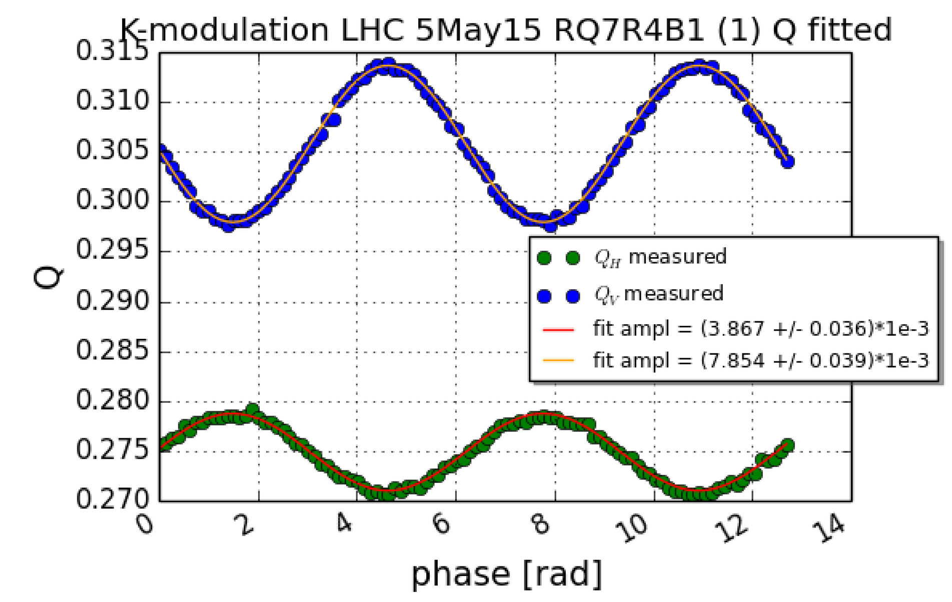
K-modulation mode	β measurement error
Step function	2.2 – 2.8 %
Sine function	0.6 – 1.8 %

Optimum modulation parameters

- Longer modulation improves measurement uncertainty.
- Frequency limited by amplitude and tune acquisition frequency (1 Hz).
- Doubling amplitude, and doubling # periods improves measurement error by 1 %.

➔Typical k-modulation measurement error: 1 - 3 %





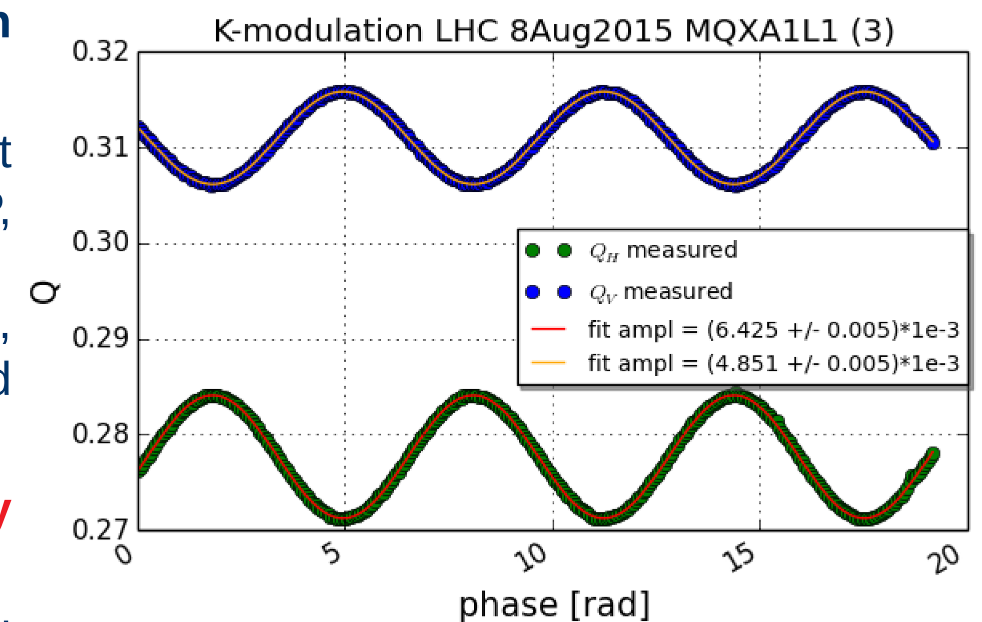
K-modulation in steps (top) and sinusoidal k-modulation (bottom) at quadrupole MQM.7R4.B1 at 450 GeV injection optics with current (red), horizontal (green) and vertical (blue) tunes with fits.

β* Measurements

80 cm β* optics measurements in IP1 (ATLAS) and IP5 (CMS):

- β fct. measurements at quadrupoles left and right of IP, then transported to IP.
- One pilot bunch per ring, modulation parameters: 10 A and 0.01 Hz.

  ➔ Measurement uncertainty and beta beat ≤ 1 %
- Measurements were repeated and found reproducible.
- Remarkable high precision measurement due to good tune signal.



β fct. measurement in IP1 of quadrupole MQXA1L1 with sinusoidal k-modulation. Horizontal (green) and vertical (blue) tunes are displayed with fits.

*Measured β**	β_{1H} [m]	β_{1V} [m]	β_{2H} [m]	β_{2V} [m]
IP1	0.81 ± 0.01	0.81 ± 0.01	0.79 ± 0.004	0.79 ± 0.01
IP5	0.80 ± 0.001	0.79 ± 0.01	0.80 ± 0.01	0.79 ± 0.002

Comparison with Turn By Turn Phase Advance Method

- Turn-by-turn: conventional method to measure β fcts. in the LHC.
- β fct. measurements at quadrupoles in LHC point 4.

➔ Results are consistent!
➔ K-modulation has smaller measurement errors.

Beta beat for β fct. measurements in LHC point 4 with the turn-by-turn phase advance method (green) and k-modulation (red) after the optics measurement correction campaign in April 2015.