FIRST K-MODULATION MEASUREMENTS IN THE LHC DURING RUN 2

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Abstract

Several measurement techniques for optics functions have been developed for the LHC. This paper discusses the first results with a new k-modulation measurement tool. A fully automatic and online 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. This paper presents the first k-modulation and β^* measurement results in the LHC in 2015. In addition, the measured beta functions will be compared to results from the turn-by-turn phase advance method.

INTRODUCTION

K-modulation is a method for measuring beta functions at locations of individually powered quadrupoles. This method is model independent and often an alternative for locations with a non-optimum phase advance between Beam Position Monitors (BPMs) for the turn-by-turn phase advance measurement [1]. A typical application is the measurement of β^* at the interaction point of a collider or the offset determination of BPMs [2]. Next to β^* measurements, it is also used in the LHC to obtain the beta functions at the transverse profile monitors close to the individually powered quadrupoles in LHC point 4.

K-MODULATION

Changing the strength of a quadruple results in a tune change. The tune change is proportional to the change of strength and the beta function at the location of the quadrupole. If the tune change can be measured accurately, the beta function can be calculated from the change in quadrupole strength following the well-known formula

$$\beta = \frac{2}{l\Delta k}\left[\cot(2\pi Q) - \frac{\cos(2\pi(Q+\Delta Q))}{\sin(2\pi Q)}\right] \quad (1)$$

where l is the length of the quadrupole, Δk the quadrupole strength change in $[m^{-2}]$, ΔQ the tune change and Q the nominal tune. Changing the strength of the quadrupole changes the tune and the beta function itself. For typical tune changes in the range of 10^{-2}, corresponding to a strength change of several 10^{-4} in the LHC, the resulting beta beat at the quadrupole location amounts to 10^{-3} - 10^{-2}. The expected maximum induced beta beat with k-modulation is in the order of 1 %.

This paper will introduce a new custom-made LHC k-modulation application that offers automated measurements and takes care of the particularities of the LHC individually powered quadrupole circuits. In addition, the first k-modulation and β^* measurement results in the LHC in 2015 will be presented. Furthermore the measured beta functions will be compared to results from the turn-by-turn phase advance method.

K-MODULATION IN THE LHC

The LHC is a superconducting hadron collider with an injection energy of 450 GeV and a design collision energy of 7 TeV per charge. The 27 km ring is designed with eight long straight sections. The matching section cells around them contain individually powered superconducting quadrupoles.

No negative voltage can be applied at the unipolar power converters of the individually powered quadrupoles. Thus a decrease in quadrupole current has to follow the slow natural current decay. The upper power converter limits of the modulation amplitude ΔI and frequency f are given by

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

with voltage ΔU, impedance Z, resistance R and inductance L. For example quadrupole MQY.5R4.B1 can be modulated with a maximum amplitude ΔI of 26 A at nominal current and 3 A at injection current at a modulation frequency of 0.1 Hz. This is well sufficient for k-modulation in the LHC. The characteristics are different for all circuits. The new k-modulation application takes care of applying appropriate parameters.

Automatic K-Modulation for LHC Run 2

For k-modulation measurements at the LHC in the past, the tune signal and the quadrupole current measurement have been combined offline. The new k-modulation tool offers simultaneous tune and quadrupole current/strength acquisition and display. It executes k-modulation in two modes: step function, where the current is trimmed to different plateaus and tune data is accumulated, and sinusoidal current modulation. Both modulation methods have been tested and the first results are presented in this paper.

The application is fully integrated into the LHC control system [3] where the circuit characteristics of the quadrupoles chosen by the user are available. The modulation frequencies, amplitudes and time over which current changes are applied are pre-calculated by the application according to the power converter limitations.

LIMITATIONS

The precision of the beta function measurement with k-modulation in the LHC is limited by tune noise. The LHC tune noise level is about 10^{-3}. According to the 2012 experience, with k-modulation in current steps, the typical measurement error on the beta function is about 10 %, mainly due

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to tune noise with multiples of 50 Hz lines in the spectrum. However, after extensive progress on the LHC tune acquisition and filtering tool, this uncertainty could be greatly reduced during Run 2. 50 Hz lines in the tune spectrum are very close to the actual tune and sometimes mistaken for the tune peak by the peak find algorithm, see Fig. 1.

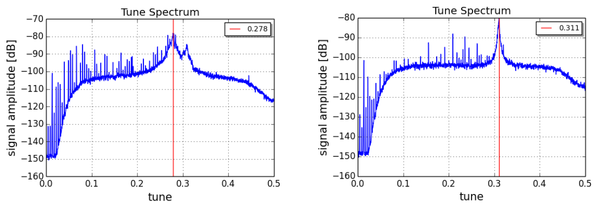

Figure 1: Tune spectrum with dominant 50 Hz lines (left) at injection tunes of nominal 0.28, and with clearer tune peak (right) at collision tunes of nominal 0.31.

The required k-modulation steps have to be significantly larger than the tune noise. Yet the maximum possible tune change is limited by the third order tune resonance in the LHC ($\Delta Q \leq \pm 0.015$ at nominal injection tunes of Q_x = 64.28 and Q_y = 59.31). Injection tunes are preferred as opposed to collision tunes when the tune separation is larger. Also the transverse damper has to be switched off during k-modulation.

Another limitation of k-modulation is that it cannot be used to obtain measured beta values during the energy ramp or the β^* squeeze. While the power converters are executing functions, they do not allow current modulation on top.

Also, k-modulation can only be carried out with low intensity beams due to tune measurement quality issues with high intensity in the machine and machine protection reasons. Parasitic measurements with physics beams are excluded. As the LHC has been found very reproducible, low intensity test fills during the start-up are, however, representative.

Effects of Hysteresis for Sinusoidal Excitation

The knowledge of the quadrupole strength change is crucial for k-modulation. The quadrupole transfer function links the quadrupole field to the current. The relative error on the measured transfer function is about 0.1 % [4]. The transfer function error on the nominal value due to hysteresis effects is about 0.2 % or smaller, corresponding to the maximum opening of the hysteresis curve [5].

Hysteresis alone would result in an error on the beta function in the order of 10^{-4}. Hence, the hysteresis effects are much smaller than the typical k-modulation measurement precision, which is in the order of 10^{-2}. For the LHC triplet magnets there is no problem of hysteresis as they are at top field during β^* measurements.

Effects of Tune Decay at 450 GeV

At the 450 GeV LHC injection plateau the superconducting magnets are at constant current which leads to a drift of the magnetic field multipoles. This changes the tune and the chromaticity. The tune decay with time is best described by a double exponential function with a fast time constant in the order of 1000 s. The tune decay component is implemented in the LHC control system as a feed forward correction to keep the tune at the reference value. [4] Still, tune decay can be observed on a small time scale, especially for measurements at the beginning of the injection plateau. For k-modulation at 450 GeV it is therefore important to correct the tune and the chromaticity after each measurement. The typical k-modulation measurement length ranges from 60 to 300 s. Thus a linear fit is used to remove the effects of tune decay.

MEASUREMENT RESOLUTION

K-modulation measurements at 450 GeV in LHC point 4 were carried out during the LHC commissioning phase in 2015. Step and sine modulations were performed on the same quadrupoles (MQM.7R4.B1 and MQM.7R4.B2) with identical amplitudes and periods to compare the measurement resolution. An example step modulation is shown in Fig. 2. The same quadrupole with sinusoidal modulation is shown in Fig. 3. In general, the measurement uncertainty is very small. The measurement error for k-modulation in steps ranges from 2.2 to 2.8 %. The measurement error for sinusoidal modulation is smaller, in the range of 0.6 to 1.8 %.

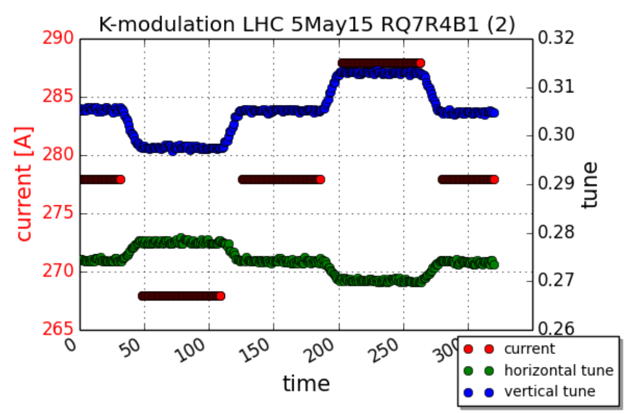

Figure 2: K-modulation in steps at quadrupole MQM.7R4.B1 at 450 GeV injection optics. The current (red) and horizontal (green) and vertical (blue) tune are displayed.

The measurement resolution also depends on the modulation amplitude, frequency and number of periods. If the tune signal is noisy a longer modulation improves the measurement uncertainty. As the frequency is limited by the given amplitude, the measurement error cannot be reduced by modulating faster. The tune acquisition frequency (1 Hz) has to be higher than the chosen modulation frequency to obtain a reasonable fit. When doubling the amplitude the measurement resolution typically improves by 1 %. The same is true for noisy tune signal and doubling the number of periods. The typical k-modulation measurement error is 1 - 3 % depending on the quadrupole. Hence, using the

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optimum modulation parameters can greatly reduce the measurement uncertainty.

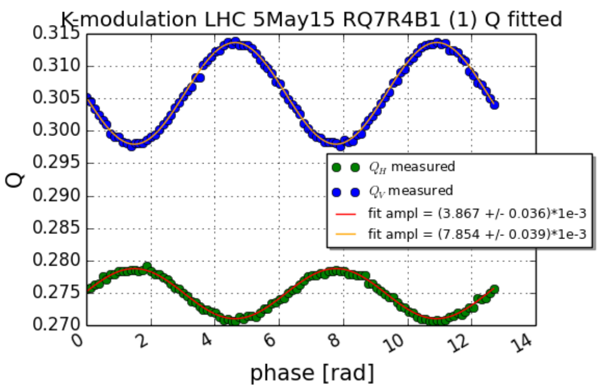

Figure 3: Sinusoidal k-modulation at quadrupole MQM.7R4.B1 at 450 GeV injection optics. The horizontal (green) and vertical (blue) tune are displayed with fits.

β^* MEASUREMENTS

For the 80 cm β^* optics the beta functions at the interaction points (IPs) 1 and 5 were measured in 2015. The quadrupoles closest to the IPs, left and right, were modulated with a sine function. One pilot bunch per beam with an intensity of about 9×10^{-9} protons was used for the modulation. The measurements were carried out after the β^* squeeze with LHC injection tunes and modulation parameters of 10 A and 0.01 Hz. No tune chirp was needed. The measured β was transported to the interaction point. An example measurement can be seen in Fig. 4. The results are listed in Table 1. The measurement uncertainty on β^* as well as the beta beat are smaller than 1 %. This remarkable high precision can be attributed to the good tune signal in the LHC. Each measurement was repeated at least once and it was found that the results are reproducible.

Table 1: Measured β^* Values in IP1/5.

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

COMPARISON WITH TURN BY TURN PHASE ADVANCE METHOD

Beta function measurement results from k-modulation and the conventional method to measure beta functions in the LHC, the turn-by-turn phase advance method, have been compared. An example analysis of the measured beta beat of quadrupoles in LHC point 4 for each method can be found in Fig. 5. The results are consistent but k-modulation has significantly smaller measurement errors.

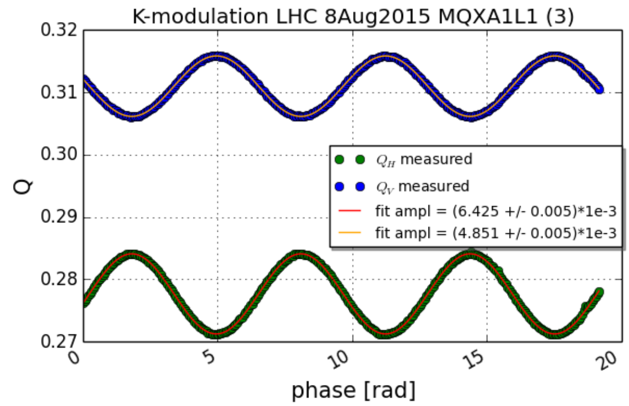

Figure 4: Beta function measurement in LHC IP1 with k-modulation. Quadrupole MQXA1L1 was modulated with a sine function with amplitude 10 A and frequency 0.01 Hz. The horizontal (green) and vertical (blue) tune are displayed with fits.

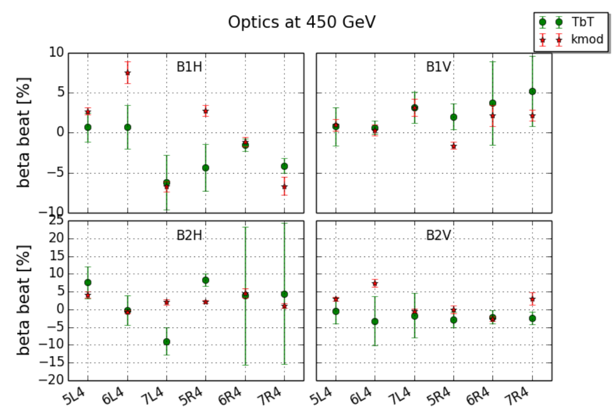

Figure 5: Beta beat for beta function measurements in LHC point 4 with the turn-by-turn phase advance method (green) and k-modulation (red) after the optics measurement correction campaign in April 2015.

CONCLUSION

K-modulation is an alternative method for measuring the beta functions at locations of individually powered quadrupoles. The method was used in 2015 to measure beta functions in LHC point 4 and in the interaction regions. A dedicated online tools is operational since the start of LHC Run 2 which simplified and sped up the measurements. The beta function measurement accuracy via k-modulation in the LHC is mainly limited by tune noise. Nevertheless, measurement errors smaller than 1 % could be achieved with sinusoidal excitation of quadrupoles. These are very promising results and pave the way for high precision beta

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function measurements at the interaction points and beam profile monitors to further decrease the emittance measurement uncertainty.

REFERENCES

[1] A. Langner and R. Tomas, “Optics Measurement Algorithms and Error Analysis for the Proton Energy Frontier,” Phys. Rev. ST Accel. Beams 18, 2015.

[2] F. Tecker, “Methods of Improving the Orbit Determination and Stability at LEP,” Ph.D. Thesis, RWTH Aachen, 1998.

[3] D. Jacque et al, “LSA - the High Level Application Software of the LHC - and Its Performance During the First Three Years of Operation,” ICALEPCS2013, San Francisco, 2013.

[4] E. Todesco et al., “Tune Variations in the Large Hadron Collider, ” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 778, pp 6–13, April 2015.

[5] M. Kuhn, “New Tools for K-Modulation in the LHC,” IPAC14, Dresden, Germany, June 2014.

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