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NEW TOOLS FOR K-MODULATION IN THE LHC

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Abstract

For many applications, the precise knowledge of the beta function at a given location is essential. Several measurement techniques for optics functions are used in the LHC to provide the most suitable method for a given scenario. A new tool to run k-modulation measurements and analysis is being developed with the aim to be fully automatic and online. It will take constraints of various systems such as tune measurement precision, powering limits of the LHC superconducting circuits and limits of their quench protection systems into account. It will also provide the possibility to sinusoidally modulate the currents of the investigated quadrupoles with a predefined frequency and amplitude to increase the measurement precision further. This paper will review the advantages and limitations of k-modulation measurements in the LHC with and without sinusoidal current modulation. The used algorithms and tools will be presented and estimates on the obtainable beta function measurement precision will be given.

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 was also extensively used in the LHC during Run 1 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}, for example $\Delta\beta_x/\beta_x \approx 0.006$ for quadrupole MQY.5R4.B1. It is therefore negligible.

This paper will introduce a new custom-made LHC k-modulation application that will offer automated measurements and online analysis and take care of the particularities of the LHC individually powered quadrupole circuits.

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 will take care of applying appropriate parameters.

The superconducting quadrupole circuits are equipped with a quench protection system (QPS). This protection system measures the voltage across the circuit and switches off the circuit in case of voltage above threshold. For QPS the sinusoidal excitation will be transparent. Figure 1 displays a quench detector output while the power converter of the corresponding circuit performs a sinusoidal current modulation. The common mode caused by sinusoidal excitation is well suppressed.

Sinusoidal current modulation of LHC quadrupoles has been tried successfully in the past in the context of BPM offset measurements [3]. Both individually powered quadrupoles and the triplets at the LHC interaction regions were modulated.

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 will

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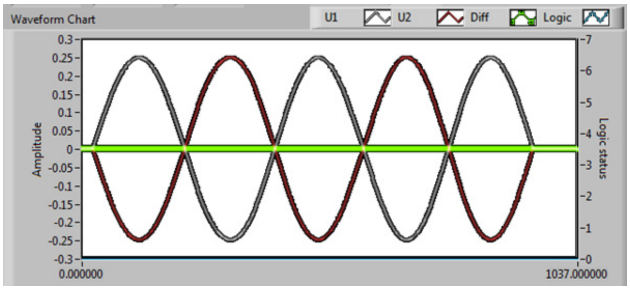

Figure 1: Quadrupole driven with a sinusoidal current of 15 A amplitude and a frequency of 0.25 Hz resulting in a maximum dI/dt of about 24 A/s. With a maximum inductance of 21 mH per coil the sinusoidal voltage is 250 mV. The green line is the voltage difference between the compared coils in the magnet which are used to detect a quench. *Courtesy J. Steckert, CERN.*

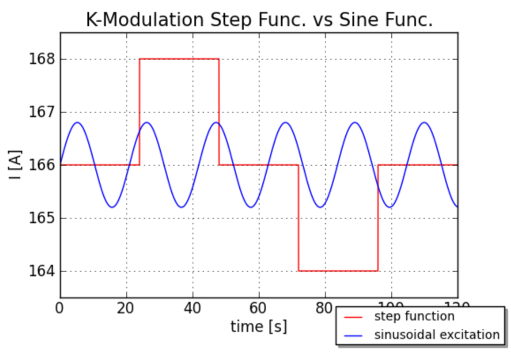

Figure 2: Step function k-modulation versus sine modulation.

offer simultaneous tune and quadrupole current/strength acquisition and display. It will execute k-modulation in two modes: step function, where the current is trimmed to different plateaus and tune data is accumulated, and sinusoidal current modulation. The two modes are illustrated in Fig. 2. Sinusoidal excitation offers the advantage of modulating several quadrupoles at the same time with different frequencies. The feasibility depends on the quality of the tune signal.

The application will be fully integrated into the LHC control system [4] and therefore will know the circuit characteristics of the quadrupoles chosen by the user. The modulation frequencies, amplitudes and time over which current changes will be applied are pre-calculated by the application according to the power converter limitations. The new tool will also offer online analysis and result display.

LIMITATIONS

The precision of the beta function measurement with k-modulation in the LHC is limited by tune noise. Figure 3 shows tune and current modulation during a k-modulation measurement of quadrupole MQY.5R4.B1 in 2012 [5]. The tune measurement has a noise level of about 10^{-3}. Note that during this measurement the transverse damper was switched off. The required k-modulation steps had to be large, in the

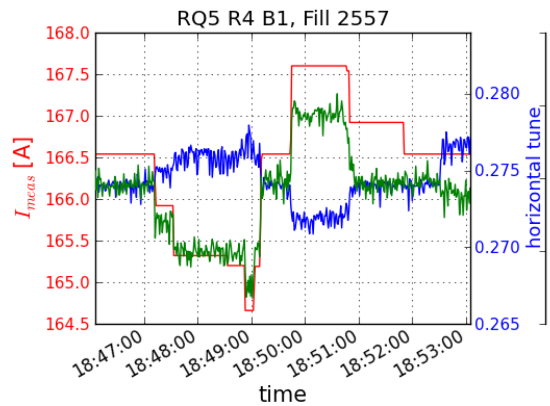

Figure 3: K-modulation measurement of quadrupole MQY.5R4.B1 during Fill 2557 in 2012. The measured quadrupole current (red) and the horizontal (blue) and vertical tune (green) are displayed.

range of 10^{-2} in tune change. 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 tunes of $Q_x = 64.28$ and $Q_y = 59.31$). In addition, the waiting time at each current plateau was about 30 s to obtain a meaningful tune average value. Thus the total measurement took about 5 - 10 minutes per quadrupole.

According to the 2012 experience, with k-modulation in current steps, the typical measurement error on the beta function is about 10 %.

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. (The current implementation of the k-modulation application does not foresee to use the real time input of the power converters.)

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 - 0.2 %. The transfer function error on the nominal value due to hysteresis effects is about 0.2 % or smaller, see Fig. 4, corresponding to the maximum opening of the hysteresis curve.

Figure 5 shows the results of a simulated sinusoidal modulation of a quadrupole in LHC point 4 assuming a tune noise of 10^{-3} and a very pessimistic maximum opening of the hysteresis curve of 23 units. The tune sampling frequency is 1 Hz and the sinusoidal oscillation frequency is 0.02 Hz. Hysteresis alone would result in an error on the beta function

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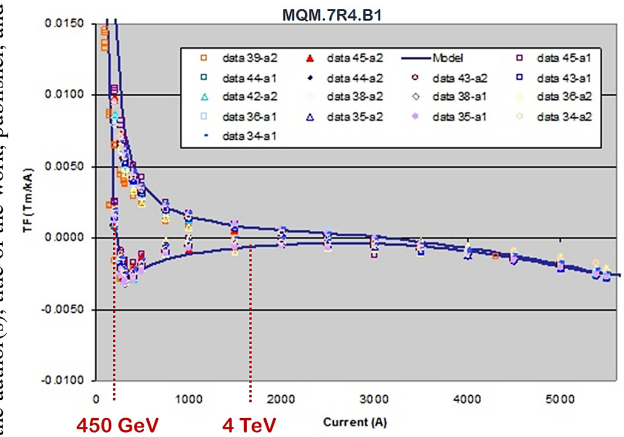

Figure 4: Measured transfer function for quadrupole MQM.7R4.B1. Dashed red lines indicate the value at 450 GeV injection energy and 2012 4 TeV collision energy. The maximum opening of the hysteresis curve is about 23 units (= 0.23 % uncertainty on the nominal transfer function). Similar for other quadrupoles in LHC point 4.

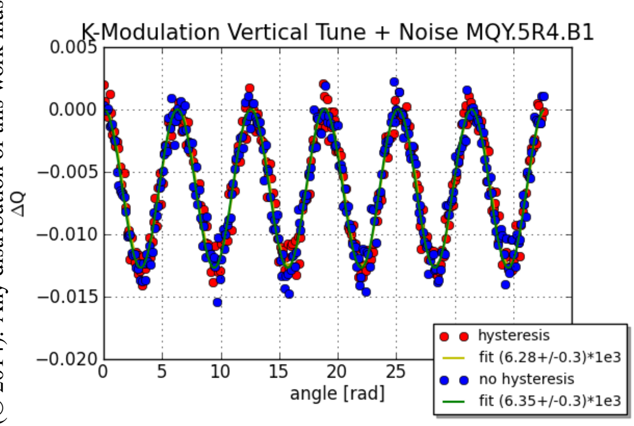

Figure 5: Simulated sinusoidal excitation of quadrupole MQY.5R4.B1 with hysteresis effects (red) and without (blue). The noisy tune response is fitted with a sine function: $\Delta Q = C + \Delta Q_0 \cdot \sin(2\pi f t)$,with offset C, amplitude ΔQ_0 and modulation frequency f. The fitted amplitude results are given.

in the order of 10^{-4}. Hence, the hysteresis effects are negligibly small. However, the total estimated error on the beta function was found to be 10 % in the simulation, mainly due to tune noise, with the currently used algorithm to obtain the beta function from sinusoidal tune modulation. The relative β error is smaller for locations with higher beta functions.

Table 1 compares the results obtained with k-modulation using current steps in 2012 during a real measurement to the simulated k-modulation using sinusoidal modulation. Currently k-modulation cannot compete with the beta function precision that can be obtained with the turn-by-turn phase advance method in the LHC. Other algorithms for k-modulation with sinusoidal modulation are still under investigation. The effect of longer measurement times will also be examined during LHC Run 2.

Table 1: Beta Function Precision with K-Modulation for Quadrupole MQY.5R4.B1 at 450 GeV Injection Energy.

	$\beta_x[m]$	$\beta_y[m]$
Model	186.05	430.99
Step fct. measured	195.67 ± 20.95 (± 10.7 %)	445.39 ± 16.52 (± 3.7 %)
Sine fct. simulated	183.99 ± 20.66 (± 11.2 %)	428.77 ± 20.34 (± 4.7 %)

CONCLUSION

K-modulation is an alternative method for measuring the beta functions at locations of individually powered quadrupoles. The method was successfully used in 2011 and 2012. But no dedicated tools were operational and the results could only be obtained offline. The beta function measurement accuracy via k-modulation in the LHC is mainly limited by tune noise and will not be better than 10 %. An online tool for this method is planned for post LS1. It includes integration into the LHC control system, tune acquisition and filtering and online analysis. It will also offer sinusoidal excitation of quadrupoles. The application will be tested in the SPS in 2014.

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