EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATOR AND TECHNOLOGY SECTOR

CERN-ATS-2011-149

Beta* Measurement in the LHC Based on K-modulation*

R. Calaga, R. Miyamoto, R. Tomas and G. Vanbavinckhove

Abstract

Accurate knowledge of the collision point optics is crucial to equalize the luminosities at the different experiments. K-modulation was successfully applied at several accelerators for measuring the lattice beta functions. In the LHC, it was proposed as an alternative method to compute the beta* at the collision points. Results of beta* measurements in the LHC based on the K-modulation technique are presented with comparisons to nominal segment-bysegment method.

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Abstract

Accurate knowledge of the collision point optics is crucial to equalize the luminosities at the different experiments. K-modulation was successfully applied at several accelerators for measuring the lattice beta functions. In the LHC, it was proposed as an alternative method to compute the beta* at the collision points. Results of beta* measurements in the LHC based on the K-modulation technique are presented with comparisons to nominal segment-by-segment method.

INTRODUCTION

Measuring the β^* via a modulation of the nearest quadrupoles to the IP is probably the least invasive and most accurate technique. A change in the integrated strength of a quadrupole ΔKL yields a change in the tunes $\Delta Q_{x,y}$ that can be unambiguously used to determine the average $\beta_{x,y}$ functions at the quadrupole, see e.g. [1],

$$\beta_{x,y} = \pm\frac{2}{\Delta KL}\Big(\cot(2\pi Q_{x,y})(1-\cos(2\pi\Delta Q_{x,y})) + \sin(2\pi\Delta Q_{x,y})\Big) \approx \pm 4\pi\frac{\Delta Q_{x,y}}{\Delta KL}\ , \qquad (1)$$

where the $\pm$ sign refers to the horizontal and vertical planes, respectively. The approximation displayed to the right of Eq. (1) is applicable for $2\pi\Delta Q_{x,y} \ll 1$ and $Q_{x,y}$ far away from the integer and the half-integer. This technique was successfully applied in the interaction regions of LEP [2]. Hadron colliders typically operate with Q_x very close to Q_y. In this case a good correction of coupling is required prior to measurements with quadrupole strength modulation. The practical application of this algorithm in the LHC consists in measuring the tune response from the left, $Q^L_{x,y}$, and the right, $Q^R_{x,y}$, quadrupoles to the IP and determining β^* via a polynomial function of the form

$$\beta^*_{x,y}(\Delta Q^L_{x,y}, \Delta Q^R_{x,y}) = \sum_{i,j=0}^{i+j<3} a_{ij}(\Delta Q^L_{x,y})^i(\Delta Q^R_{x,y})^j \qquad (2)$$

where the coefficients a_{ij} have been precomputed with simulations. A similar polynomial expression is used for the waist location. Error propagation from the tune measurement is straight forward for these polynomials. The next sections report on the K-modulation measurements at β^*=1.5 and 90 m.

β^*=1.5 M

An illustration of the computation of the coefficients a_{ij} for the case with β^*=1.5 m is shown in Fig. 1. The effect of the quadratic terms are clearly visible. The quality of the fit can be regarded as perfect with a $\chi^2 < 10^{-6}$.

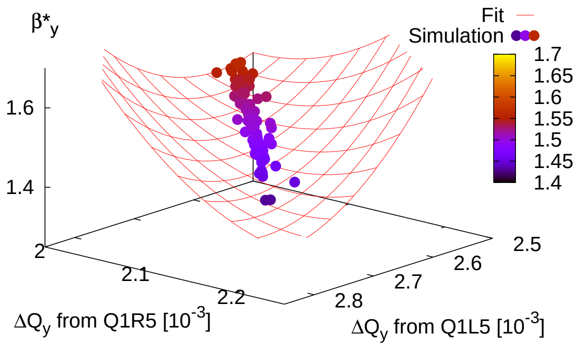

Figure 1: IP5 vertical β^* versus tune-shifts from a change of $\Delta K = 10^{-5}$ m^{-2} in the left and right Q1 quadrupoles. The nominal lattice has β^*=1.5 m and random errors around the ring are considered.

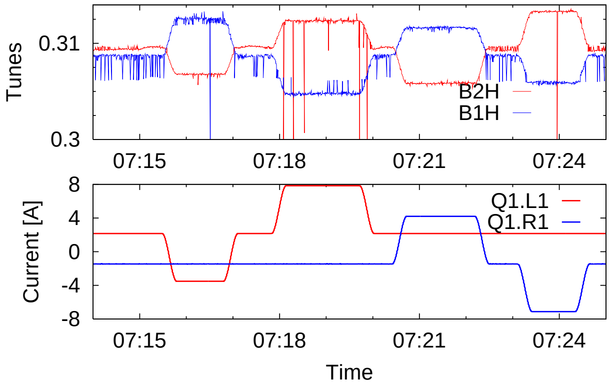

Figure 2: Beam 1 and Beam 2 horizontal tunes measurements (top) during modulation of the IR1 Q1 right and left quadrupole strengths (bottom).

An illustration of the tune measurement during the K-modulation process is shown in Fig. 2. The tune data is noisy with spurious peaks around the tunes in the Fourier spectra. Appropriate cuts in the tune histograms can be used to partially remove the spurious peaks during the quadrupole current plateaus. Figure 3 illustrates the cleaning process with a typical histogram of the horizontal tune. Figure 4 shows a histogram of the achieved tune resolution for all the K-modulation measurements during 2011.

Table 1 shows the measured β^* after the optics corrections. The maximum relative deviation between model and

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[*] This work is partially supported by the DOE under US LARP

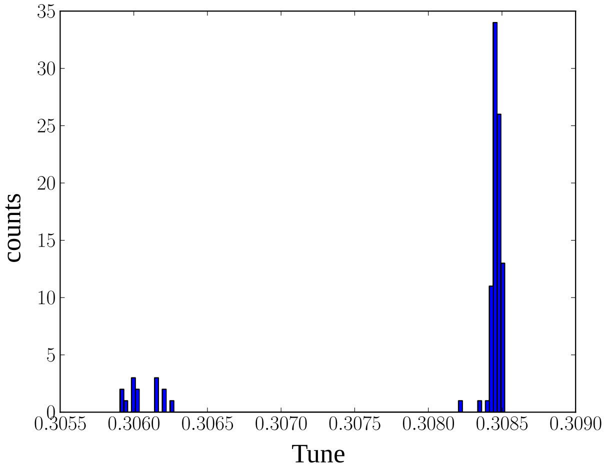

Figure 3: Illustration of a typical histogram of the tune measurement during about one minute without quadrupole changes. Clear spurious tunes measurements are observed requiring cleaning.

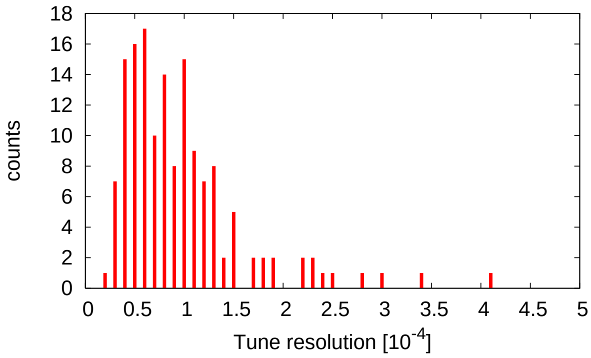

Figure 4: Tune resolution histogram for the 2011 K-modulation measurements after filtering the spurious data.

measured β^* is about 6%. Typically, resolutions between 3% and 5% are achieved. The luminosity imbalance from these measurements is (4 ± 4)%, compatible with zero and consistent with the luminosity measurements.

To assess the effect of hysteresis the same modulation was applied to Q1 right of IP5 after one hour of K-modulation measurements. Figure 5 shows no hysteresis effects.

Table 1: β^* measurements with K-modulation at β^*=1.5 m after filtering bad tune measurements.

	IP5		IP1	
Beam/Plane	β^* [m]	error [%]	β^* [m]	error [%]
B2H	1.48	3	1.59	3
B2V	1.53	3	1.59	3
B1H	1.50	3	1.55	4
B1V	1.51	4	1.52	5

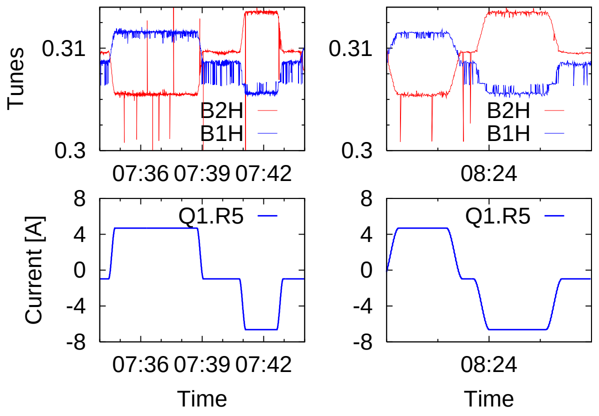

Figure 5: Illustration of the absence of hysteresis effects showing identical tune measurements after 1 hour of K-modulation.

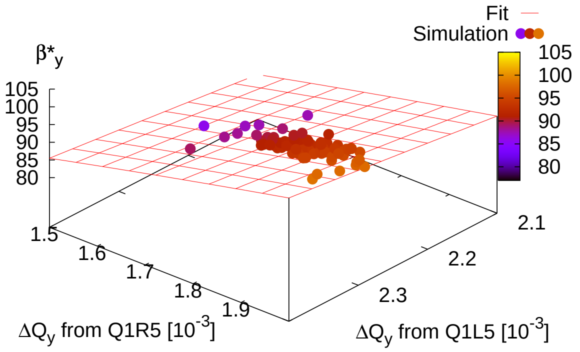

Figure 6: IP5 vertical β^* versus tune-shifts from a change of $\Delta K = 4 \times 10^{-5}$ m^{-2} in the left and right Q1 quadrupoles. The nominal lattice has β^*=90 m and random errors around the ring are considered.

β^*=90 M

TOTEM [3] and ALFA [4] request the best possible control and knowledge of the optics in the IR. Dedicated Machine Development (MD) time has been devoted to measure and commission the optics with β^*=90 m. Prior to the experiment the tune response of the Q1 quadrupoles is studied for small variations in β^*. Figure 6 shows the IP5 β^*_y versus tune-shifts from a change of $\Delta K = 4 \times 10^{-5}$ m^{-2} in the left and right Q1 quadrupoles for an ensemble of machines with different optics errors. This allows for the computation of the a_{ij} coefficients of Eq. 2. Opposite to the β^* =1.5 m case, a very linear behavior is observed.

During the 1st MD [5] the AC dipole was used to measure the β function around the accelerator. This served to compute the correction for the 2nd MD. This correction is stored in two knobs

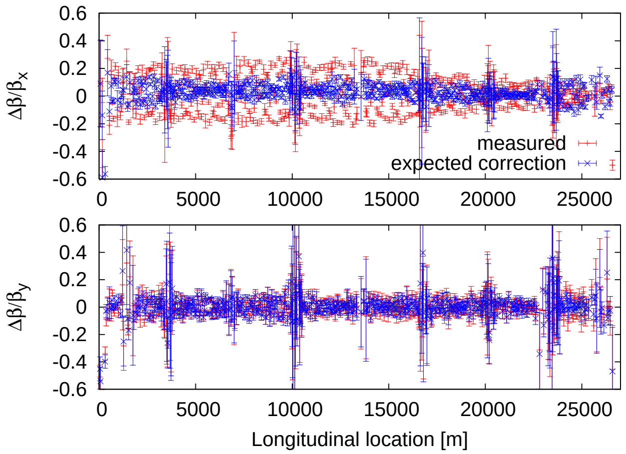

Figure 7: Beta-beating for Beam 1 as measured and as expected from the computed correction.

named “local_knob_beta_b1_90m_2011” and “local_knob_beta_b2_90m_2011” for Beam 1 and Beam 2, respectively. Figure 7 shows the Beam 1 β-beating before correction and the expected effect of the correction. Unfortunately the AC dipole was not available during the 2^{nd} MD and it was not possible to confirm the effect of the correction.

K-modulation measurements were performed before and after trimming the above mentioned correction knobs. An illustration of the tune measurement during the modulation of the quadrupole strengths is shown in Fig. 8. The modulation depth was considerably increased with respect to previous measurements to achieve the best possible resolution. However Beam 2 data is severely affected by noise and possibly coupling (although with very low closest tune approach as seen in Fig. 8).

Table 2 shows the Beam 1 β^* and waist (w^*) measurements before and after trimming the correction knob. The better resolution in both quantities thanks to the larger modulation depth is clearly observed, reaching a minimum relative error of 1.6% for the β^*. The correction has no effect on the measured β^* values, while it seems to shift the waist location further from the IP for some cases. This behavior is unexpected and requires further investigation.

CONCLUSION & OUTLOOK

K-modulation of the nearest quadrupoles to the IP is the preferred technique to determine the β^*. We have demonstrated that using appropriate cuts and using a large modulation depth a minimum resolution of 1.6% was achieved. This resolution might be further improved by applying a larger beam excitation to better observe the tunes or using the PLL. Further separating the horizontal and vertical tunes would allow for even larger tune-shifts. The automation of the full procedure is currently being implemented and will allow for faster measurements.

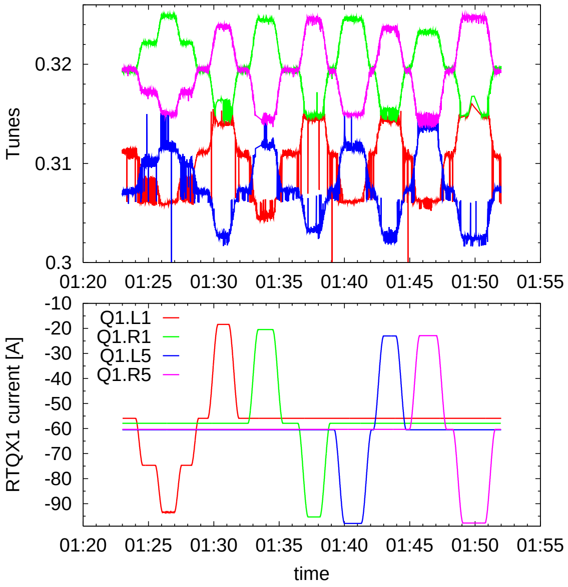

Figure 8: K-modulation in IR1 and IR5 Q1 quadrupoles for β^*=90 m.

Table 2: β^* measurements with K-modulation at β^*=90 m after filtering bad tune measurements.

	IP5			IP1		
Beam-Plane	β^* [m]	err [%]	w^* [m]	β^* [m]	err [%]	w^* [m]
B1H	85	1.7	-9±2	79	5	0±5
B1V	83	1.8	23±2	82	3	8±3
After correction						
B1H	85	1.6	-22±2	77	2	-6±2
B1V	84	2	33±3	84	1.9	-4±2

ACKNOWLEDGMENTS

We thank all the operation crew, H. Burkhardt and R. Steinhagen for their help during the experiments.

REFERENCES

[1] M. Minty and F. Zimmermann, “Measurement and control of charged particle beams”, published by Springer, 2003.

[2] G. Buur, P. Collier, K.D Lohmann and H. Schmickler, CERN SL 92-15 DI.

[3] TOTEM Collaboration, G. Anelli et al, “The TOTEM experiment at the CERN LHC”, JINST 3 (2008) S08007.

[4] ATLAS Luminosity and Forward Physics Community, “ATLAS Detectors for measurement of Elastic Scattering and Luminosity”, CERN LHCC-07, 2007

[5] H. Burkhardt et al, “Un-squeeze to 90 m”, CERN-ATS-Note-2011-032 MD (LHC).