MEASUREMENT OF OPTICAL FUNCTIONS IN HERA

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Abstract

The linear optics of both HERA electron and proton ring have been measured with several methods, including gradient changes in individual powered quadrupoles, local orbit changes in the arc sextupoles and dispersion measurements. A combination of these methods is necessary for a thorough check of the linear optics. Automated data taking and analysis has proven to be an important tool in that respect and revealed several optics errors. A review of the methods and results of the measurements will be presented.

1 INTRODUCTION

The interaction regions of the HERA lepton-proton collider have been upgraded to increase the luminosity. The upgrade included a reconstruction of the interaction regions [1] in both the lepton (HERA-e) and proton (HERA-p) ring. In addition the HERA-e optic in the arcs was changed to decrease the horizontal emittance.

During the re-commissioning of HERA a number of automated measurements have been used to routinely determine the optical functions of both rings. This paper describes the direct measurement of β and dispersion functions. Results from response matrix fitting are described in a separate contribution [2].

2 MEASUREMENT OF β-FUNCTIONS AT INDIVIDUAL QUADRUPOLES

The new interaction regions of HERA are equipped with a large number of individually powered quadrupole magnets. They provide the flexibility of the electron beam optics and the handling of both the lepton and proton beam in the interaction area. These magnets can be used to investigate the β-functions close to the interaction point (IP).

The measurement was performed in the usual way: The strength of a single powered quadrupole is changed in small steps and the resulting variation of the betatron tune is observed. This change is proportional to the β-function at the quadrupole. For higher accuracy of the measurements the nonlinear behavior of the excitation curve of the magnet due to saturation effects has been taken into account.

As an example the result of a series of such measurements is plotted in Fig. 1.

The line shows the theoretical β-function in the vertical plane of the proton ring close to the IP North. The measured data are represented as crosses in the graph. All measured values are smaller than the theoretical predictions, indicating an optics problem. In consistence with the measurements of β-beating in the arcs (see below) an error in the calibration of a proton quadrupole could be detected.

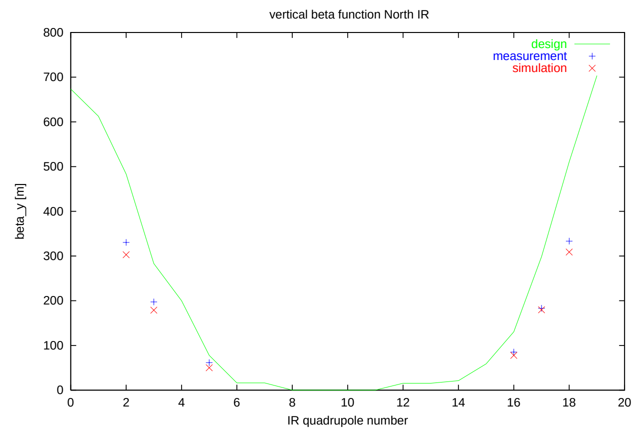

Figure 1: HERA-p β-function measurement at individual quadrupoles in the North interaction region.

The calculated β-function including this error is shown as stars and is in good agreement with the measured data.

3 MEASUREMENT OF β-FUNCTIONS IN THE ARCS

The measurement of β-functions in the arcs of the HERA lepton- or proton ring cannot be performed by changing individual quadrupoles, as all quadrupoles are powered in series. A measurement of the β-beat is nevertheless possible by applying local closed orbit bumps which change the orbit in the sextupoles. The resulting betatron tune change is

$$\frac{\Delta Q}{\Delta x} = \frac{1}{4\pi}\int_{s_1}^{s_2} \beta(s)m(s)\frac{\Delta x_{c.o.}(s)}{\Delta x}ds \qquad (1)$$

with $m(s)$ being the sextupole strength at position s, $\Delta x_{c.o.}(s)/\Delta x$ the change in the closed orbit normalized to the bump amplitude and the integral is evaluated between the beginning s_1 and end s_2 of the bump.

In addition to the change of the betatron tune by orbit changes in the sextupoles a change of energy occurs due to path lengthening. For HERA the contribution to the betatron tune change is small enough to be neglected.

Fig. 2 shows the horizontal and vertical betatron tune as a function of the bump amplitude for 8 subsequent closed bumps in the HERA NR octant.

The HERA arcs have a FODO lattice with 90° (HERA-p) resp. 72° (HERA-e) phase advance per cell. Each cell has only one horizontal and one vertical corrector. Successive closed 3-bumps can thus be applied with a phase difference of 90° resp. 72°. For a section of the optics with

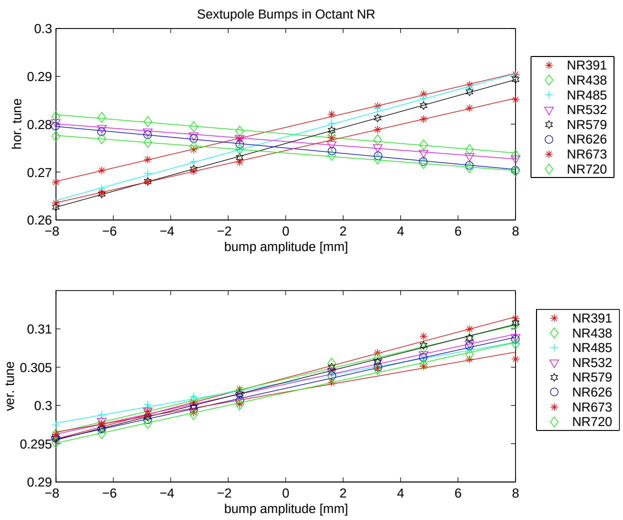

Figure 2: Horizontal betatron tune (upper) and vertical betatron tune (lower) versus bump amplitude for 8 different bump locations in the NR octant.

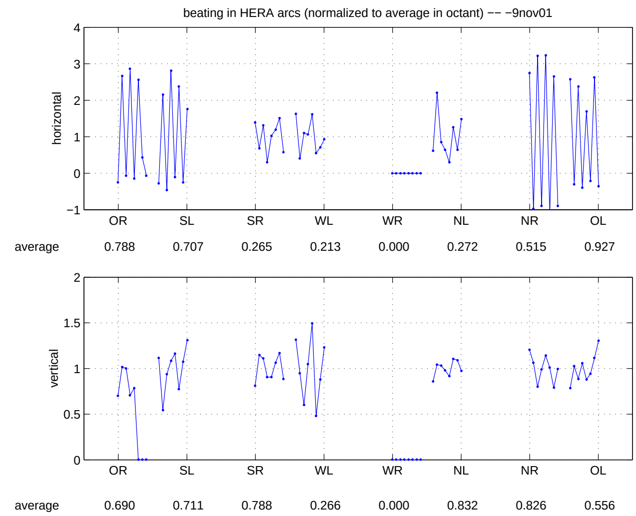

Figure 3: Normalized slope of horizontal (upper) and vertical (lower) betatron tune change versus bump amplitude in the HERA proton ring octants.

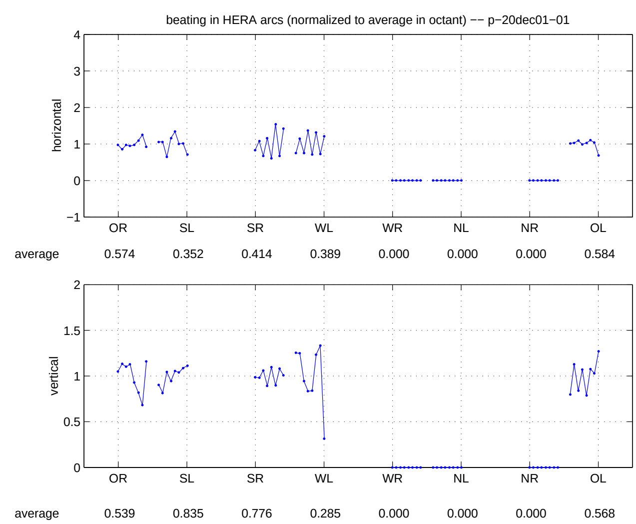

Figure 4: Normalized slope of horizontal (upper) and vertical (lower) betatron tune change versus bump amplitude in the HERA proton ring octants. This measurement was performed after an optics correction.

no optical errors within this section[1] the β-beat oscillates with twice the phase advance. In HERA-p this method can thus only detect the cosine-like contribution to the β-beat.

To have a model independent representation of the measurements, the slope obtained from curves like the ones in Fig. 2 is normalized by the average slope of all measurements in one octant. This is equivalent to calculating

$$\frac{\Delta Q_i/\Delta x}{\langle \Delta Q/\Delta x \rangle} = 1 + \frac{\int_i \Delta\beta(s) m(s) \frac{\Delta x_{c.o.}(s)}{\Delta x} ds}{\left\langle \int \beta(s) m(s) \frac{\Delta x_{c.o.}(s)}{\Delta x} ds \right\rangle} \qquad (2)$$

with ΔQ_i the betatron tune change due to the ith bump and $<>$ the average of all bumps in one octant. This is a measure for the β-beat and is 1 in case of the design optic.

The data is automatically taken and analyzed using a MATLAB [3] application based on the low level functions from the HERA-Toolbox [4].

Results for the proton machine are shown in Fig. 3. A huge beating can be observed. Simulations showed that this typical pattern can be explained through a wrongly calibrated quadrupole in the interaction region.

After correcting the quadrupole setting, the beating in the arc is reduced, as shown in Fig. 4. The residual β-beat is approximately 20%.

Corresponding results for the electron ring are shown in Fig. 5, indicating a β-beat of approximately 20-30%.

4 DISPERSION FUNCTION

For optimizing the luminosity of HERA, the dispersion function $D(s)$ has to be zero at the two interaction points at H1 and ZEUS both for HERA-e and HERA-p.

$D(s)$ was measured in the standard way by changing the RF-frequency $f_{\rm rf}$ and measuring the orbit change Δx, which is related to the dispersion by $\Delta x = D_x \frac{\Delta p}{p}$ using the relative momentum change

$$\frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha_{\rm c}\right)^{-1} \frac{\Delta f_{\rm rf}}{f_{\rm rf}}\,, \qquad (3)$$

where $\alpha_{\rm c}$ is the momentum compaction factor. An analog expression can be obtained for the vertical plane.

The additional $1/\gamma^2$ term only contributes significantly in the case of the proton ring. Fig. 6 shows as an example the measured dispersion function for HERA-e before it was

[1]This assumption is experimentally verified by ensuring that the 3-bump based on the theoretical optics shows no orbit deviation beyond the third involved corrector.

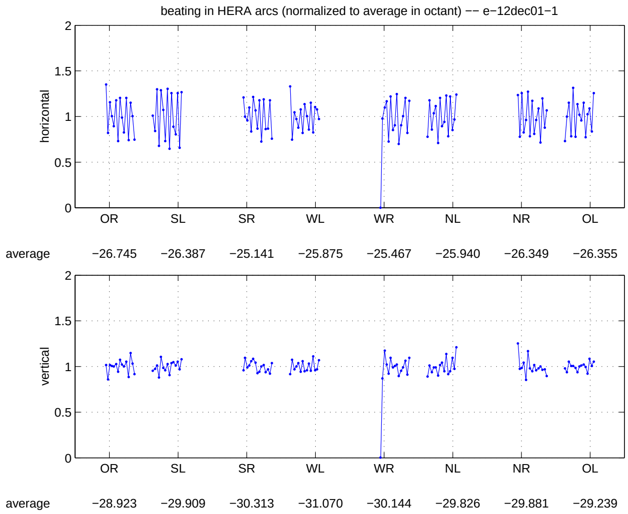

Figure 5: Normalized slope of horizontal (upper) and vertical (lower) betatron tune change versus bump amplitude in the HERA electron ring octants.

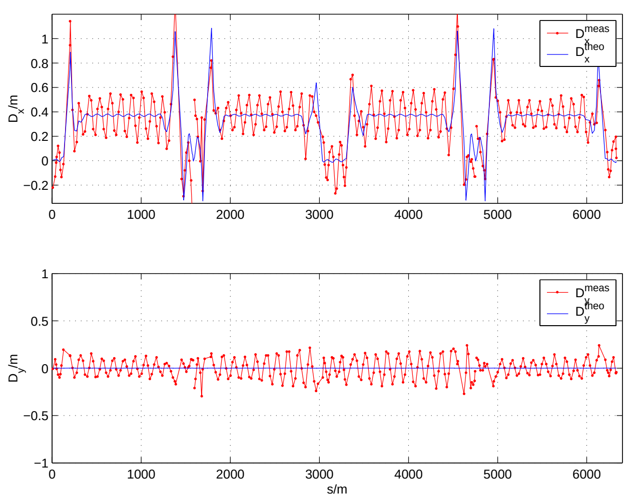

Figure 6: Theoretical and measured dispersion functions before correction at HERA-e.

corrected. The data were automatically obtained using the HERA-Toolbox [4].

A large dispersion beating was observed coming from one of the IPs of HERA. Using the technique of fitting the dispersion beating upstreams and downstreams from the IP (Fig. 7), it was possible to localize the source of the dispersion beating: One of the superconducting final focus quadrupoles on the left side of the IP. After realigning this quadrupole [5] the distortion of the dispersion originating at this IP vanished.

5 CONCLUSION

Automation of direct methods to measure the optical functions have been a valuable tool during the recommissioning of HERA. The advantages of the described

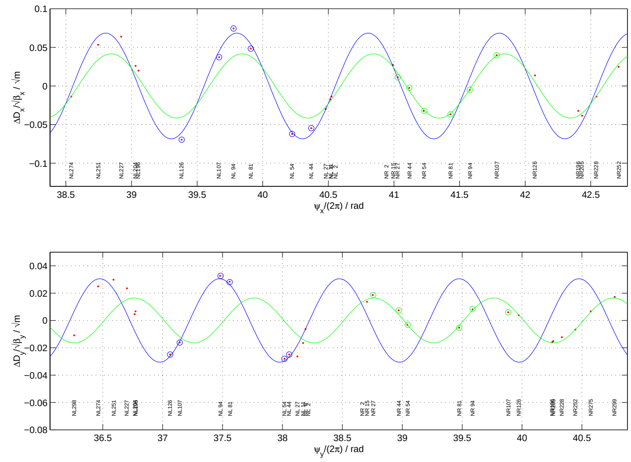

Figure 7: Fitted dispersion functions in normalized coordinates at one of the IPs at HERA-e.

methods are their robustness and the easy interpretation of the results. But only the full automation of the data taking and analysis allows the repetitive use of these measurements with reliable and comparable results. The easy operation enables operators to perform optic measurements even on owl-shifts with direct interpretation of the results, thus ensuring a fast detection of optics errors or diagnostic failures.

6 REFERENCES

[1] M. Seidel, "The upgraded interaction regions of HERA", DESY-HERA-00-01.

[2] G. Hoffstaetter, J. Keil, A. Xiao, "Orbit-Response Matrix Analysis at HERA", this conference

[3] MATLAB, "The Language of Technical Computing", The Mathworks Inc., 3 Apple Hill Drive, Natick, MA 01760-2098

[4] W. Decking, J. Keil, T. Limberg, "HERA-Toolbox", www.desy.de/matlab

[5] F. Brinker, W. Decking, G. Hoffstaetter, J. Keil, T. Limberg, M. Minty, M. Seidel, R. Wanzenberg, F. Willeke, "Beam Based Alignment of Combined Function Magnets in the Upgraded HERA Interaction Regions", this conference