A TUNE FEEDBACK SYSTEM FOR THE HERA PROTON STORAGE RING

S. Brinker, S. W. Herb, F. J. Willeke, DESY, Hamburg
T. Lohse, Humboldt University Berlin, Berlin

Abstract

The betatron tunes of a circular accelerator are important parameters which have to be controlled and adjusted continuously during beam operation in order to assure good experimental background conditions. For the HERA proton storage ring, persistent current effects of the superconducting magnets are the main source for the insufficient reproducibility of the tunes during acceleration of the proton beam without a feedback. A tune feedback has been developed, implemented and tested during beam acceleration and luminosity operation. Considering the different conditions during energy ramps and luminosity runs, two versions of this feedback system have been established based on different correction and peak-finding algorithms (e.g. wavelet analysis). No additional excitation is needed on top of the standard tune indication system in HERA. The tunes could be kept constant during beam acceleration with a standard deviation of $\Delta Q = 0.002$. In luminosity runs where the tune control is more critical, first tests resulted in a standard deviation which was a factor of ten smaller.

The feedback system is implemented as a standard tool for beam acceleration.

THE ALGORITHM USED DURING BEAM ACCELERATION

Operating Conditions

The tune indication system of the HERA proton ring is described in [1]. The values of the tunes are determined by the analysis of the FFT-spectrum using a peak finding algorithm. The beam is normally excited during injection and acceleration by a repetitive chirped waveform which provides unambiguous tune signals for the operators but does not result in significant emittance growth. The feedback algorithm was used with these standard excitation levels. Most of the tune stabilization during acceleration is accomplished using correction tables based on the archived values of corrections inserted by the operators during previous energy ramps. The algorithm must then cope with residual non-repeatability from sources such as the persistent currents in the superconducting coils. Therefore the deviation between the actual tunes and the desired values is rather small and develops slowly in time so that the algorithm can be designed to be safe and reliable rather than quick.

The effects of crossplane coupling have to be taken into account. The strong sextupoles embedded in HERA to compensate chromaticity are one major source. Small errors in their alignments and vertical orbit displacements result in skew quadrupole fields. During the energy ramp the working point of HERA is mostly set close to the coupling resonance ($Q_x = 0.298$, $Q_y = 0.291$) to guarantee good beam lifetime. So the separation of the tunes is small and even with low coupling, two peaks of similar height are often visible in both vertical and horizontal tune spectra. The identification of the tunes is not trivial and in the design of the algorithm this common situation had to be taken into account.

Description of the Algorithm

The first requirement was to control the tunes during the acceleration of the proton beam. As it can not be assumed that the peaks in the spectra are clearly identified the algorithm does not control the single tunes but their sum and difference. Correcting the sum does not require an identification of the tunes, but sets the tunes roughly to their desired values. In a second step the difference is adjusted. For this operation the peaks of the spectra have to be associated with the horizontal tune (Q_x) and the vertical tune (Q_y). To check the identification a test was implemented within the algorithm: The quadrupole correction strengths are changed so that the separation of the tunes should increase if they are correctly identified. If the separation decreases, the quadrupole strengths are changed further until it again increases. The number of these tests should be minimized during operation as the tunes are disturbed.

The tunes are measured with a frequency of 2 Hz. The last 9 values are stored in a buffer. One parameter of the algorithm is the number of measurements used to calculate the arithmetic mean of the tunes. The standard value is set to three. Another parameter is the gain. The standard value is set to 0.75. The third parameter affects the time dependence by varying the time intervals between the requests to change the strengths of the quadrupoles. The standard value is 1.5 sec. All parameters and the desired values of the tunes can be modified at any time by the operator.

In order not to apply false corrections, the algorithm remains inactive if the tune measurement is disturbed or inconclusive (the error of one tune mean value exceeds a maximum error or sum of both errors is larger than the distance between the tunes).

The operator can change the tunes manually at any time; the tune controller recognizes any interference, stops immediately and restarts five seconds after the last manual change.

Test of the Algorithm

The stability of the algorithm was tested during machine operation:

- horizontal and vertical tunes were exchanged
- the desired tunes were exchanged (Fig. 2)
- one tune (Fig.1)
- or both tunes were changed drastically

In all cases the desired values of the tunes were re-established. Figure 1 shows how the algorithm is working: If just one tune is off from its desired value, the average tune is corrected first thereby increasing the deviation of the second tune from its desired value. This is tolerable as the tunes can vary somewhat without disturbing beam quality during energy ramps.

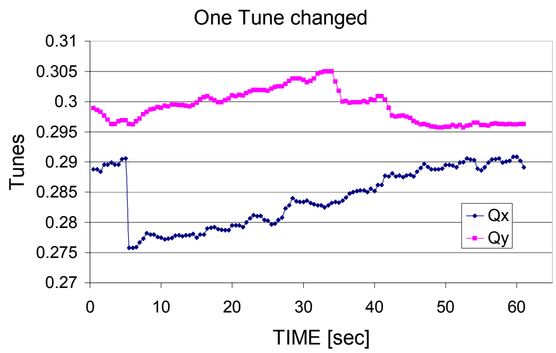

Figure 1: Reaction of the algorithm to the change of one tune.

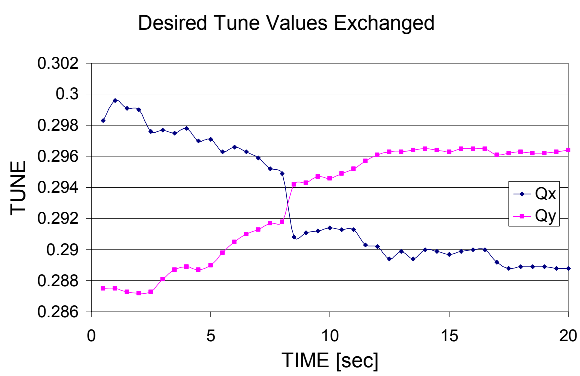

Figure 2: Reaction of the algorithm to the exchange of desired values of the tunes.

Adaptation of the Limits during the Ramp

The proton beam is injected into HERA with an energy of 40 GeV. At this energy the smallest possible current change of the quadrupoles corresponds to a tune change of 0.0008. While the beam is accelerated to the final energy of 920 GeV the smallest possible change decreases to 0.00001. The algorithm takes this fact into account by decreasing the tolerated deviation from the design values in four steps from 0.002 to 0.0001.

Results

The tune controller has been used as a standard tool during HERA energy ramps for about one year. No ramp failed due to the controller. In Fig. 3 a typical plot of the transverse tunes during an energy ramp is shown. During the first half of the ramp the tunes are more unstable. In April 2006 the tune controller was used during 35 ramps. Over all ramps, the deviations of the horizontal (vertical) tune from the target values had an r.m.s. spread of 0.0019 ± 0.0003 (0.0017 ± 0.0003). During these energy ramps the maximum difference between the actual value of Q_x and the desired value did not exceed a value of 0.014 (0.018 for Q_y) which may be compared with an allowed tune deviation of about 0.025.

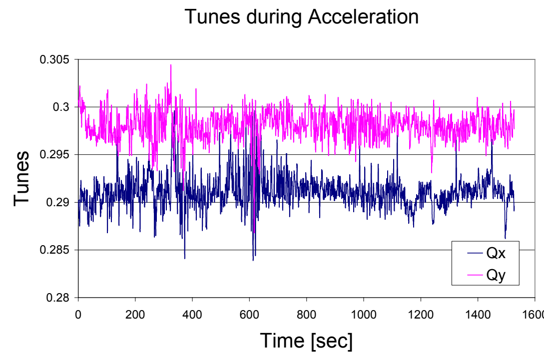

Figure 3: The tunes during acceleration.

TUNE FEEDBACK DURING LUMINOSITY RUNS

The Algorithm used for Luminosity Operation

The correction mode used during energy ramps is not suitable for luminosity runs; unnecessary tune movement must be avoided since it can result in drastic changes in the proton induced background of the experiments in HERA. As coupling can be assumed to be corrected, the tunes are well identified and the algorithm can correct the tunes directly in this case instead of the sum and the difference values. The number of the averaged values is increased to 10 and the interval between two correction steps is set to 5 seconds. Both parameters can be changed online if necessary.

Wavelet Analysis of the Spectra

In this method the spectra are filtered and smoothed using wavelet analysis to improve the precision and reliability of the tune detection. Wavelet decomposition is a known method for analysis of localized signals. A set of wavelets is obtained by scaling and translation of the so called “mother wavelet”, a function localized in space and frequency. For the analysis of the spectra, the Daubechies wavelets with tight compact support of 4 bins (Daub4) [2] have been chosen due to their supreme regularity properties.

In the algorithm, the components are sorted according to their amplitude. For the inverse transformation, in order to smooth the spectra, only the largest 30% of the components are used. Additionally all contributions of the most localized wavelets are filtered out to reduce small scale noise. Then the maxima, the height above background and the width of the signal are determined. In addition, from the analysis of wavelet contributions at different scales, the crossplane coupling, compared to the direct signal, is estimated. The parameters were optimized empirically. The method is described in [3].

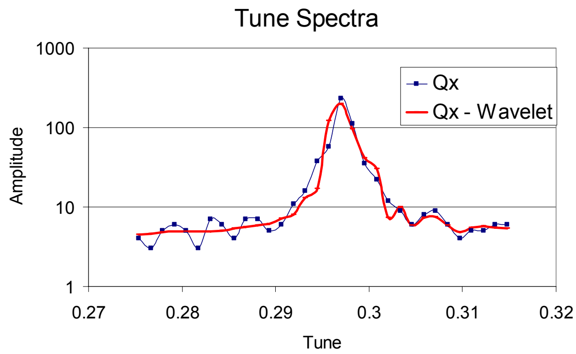

Figure 4: Comparison of raw and filtered tune spectrum.

Results

The functionality of the algorithm has been successfully tested using tests similar to those described for the energy ramp algorithm (change of the tunes by the operator, change of the design tunes, etc.).

During a luminosity run a standard deviation of less than $\Delta Q = 0.0001$ was achieved. The maximum deviation of the tunes from the design values was 0.0002.

PROSPECTS

Up to now the algorithm uses the peaks of the spectra to correct the tunes by steering quadrupole coils. The algorithm can be expanded to make use of other information contained in the spectra such as the width (chromaticity) and height of the signal above background. If coupling is not corrected there are two peaks in both spectra. The ratio of the peak height of the coupled signal relative to that of the direct signal can vary between 1 (completely coupled) and 0 (no coupling). The square root of the product of the two ratios (called coupling factor) and the separation of the tune peaks are used as a measure of the amount of coupling. Two skewed quadrupoles are embedded in HERA for the correction of the crossplane coupling.

The basic idea of an algorithm for the correction of the coupling is to minimize the separation of the tunes using the normal quadrupoles in a first step. Then the coupling is reduced by steering the skewed quadrupoles. For this step a scaling function was defined using the separation and the coupling factor. The steps can be iterated if necessary. The first part was implemented and tested successfully. To test the second step the coupling was corrected and both tunes were set to the same value. Then coupling was generated by changing the strength of the skewed quadrupoles. Fig. 5 shows the coupling factor while the algorithm successfully minimized the coupling.

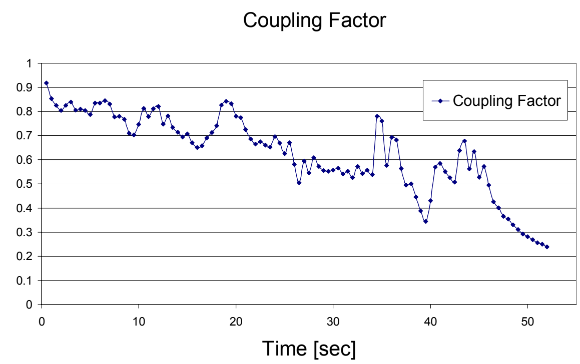

Figure 5: Change of the coupling factor while minimizing the crossplane coupling.

Further investigations are necessary to improve the algorithm (scaling function, timing, etc.) as its reliability is not sufficient up to now (Fig. 6). In Fig. 6 the correlation between the coupling factor and the tune separation can be seen.

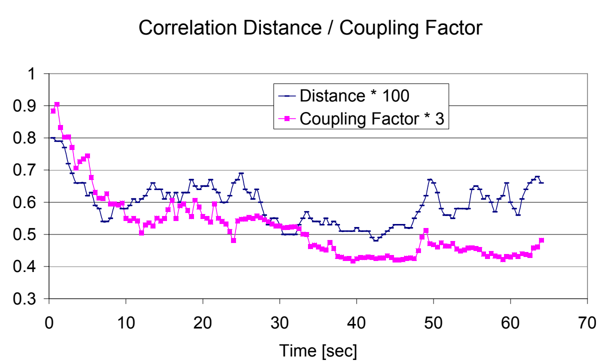

Figure 6: Tune separation and coupling factor

REFERENCES

[1] S. Herb, “Betatron tune measurement system for the PETRA and HERA proton storage ring”, Kerntechnik, Carl Hanser, 1991.

[2] W.H. Press et al., Numerical Recipes, Cambridge Univ. Press, 1992.

[3] T. Lohse, “Model Independent Analysis of HERA Proton Tune Spectra”, http://www-eep.physik.hu-berlin.de/~lohse/tunes/tunes.ppt, 2002