Diffusion-like Processes in Proton Storage Rings due to the Combined Effect of Non-Linear Fields and Modulational Effects with more than one Frequency

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Abstract

An analysis of the non-linear particle dynamics in hadron storage rings shows that the combined effect of non-linear fields and a tune modulation with more than one frequency component leads to enhanced emittance growth. In the proton storage ring of HERA, a fast harmonic tune modulation is caused by ripples in the power supplies and a slow tune modulation by the ground motion in the HERA tunnel. By recognizing the damaging effect of the fast tune modulation, one could attempt to compensate for the fast frequency components by generating an additional external tune modulation with the same frequency but with a 180° phase difference. The following work summarizes the results of two diffusion experiments in the proton storage ring of HERA which analyzed the possibilities for a compensation of harmonic frequency components in the power spectrum of the proton loss rates.

1 INTRODUCTION

The beam-beam interaction in the hadron-electron collider HERA is a source of strong non-linear fields and leads to a proton diffusion at $820GeV$. Under the combined influence of the beam-beam resonances and an additional tune modulation, the proton single particle dynamics leads to a slow emittance growth. Because the proton dynamics has virtually no damping, such a particle diffusion can spoil the long-term stability of the protons and might limit the beam lifetime. In order to achieve a sufficiently large beam lifetime during the luminosity operation, the working point of the proton beam should not lie near a low-order resonance.

The working point of the proton beam in HERA is located between the 7^{th} and 10^{th} order betatron resonances. Without tune modulation, the resonance condition can be written as

$$l \cdot Q_{x,p} + m \cdot Q_{y,p} + p = 0, \quad l, m, p \in \mathbf{Z}, \qquad (1)$$

and the area between the 7^{th} and 10^{th} order resonances contains no low-order resonance lines. Thus, one expects a large beam lifetime for any working point between the 7^{th} and 10^{th} order resonances. The diamond shape in Fig.1 shows a typical working point of the proton beam in HERA during luminosity operation.

In the case of a harmonic tune modulation, the resonance condition reads

$$l \cdot Q_{x,p} + m \cdot Q_{y,p} + n \cdot \frac{f_{mod}}{f_{rev}} + p = 0, \quad l, m, n, p \in \mathbf{Z}, \qquad (2)$$

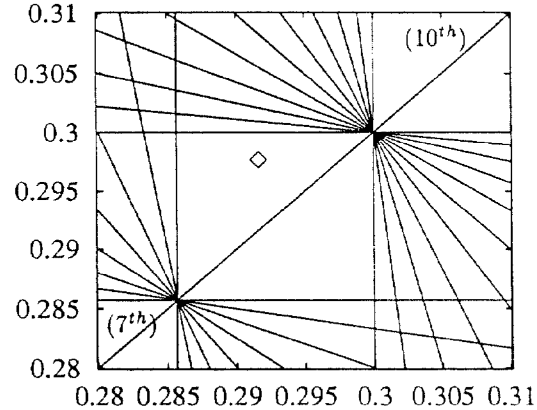

Figure 1: *The transverse tune diagram without any tune modulation. The diamond shape shows a typical working point of the proton beam in HERA during luminosity operation.*

and a tune modulation leads to a set of additional resonance sidebands. f_{mod} is the modulation frequency and f_{rev} the revolution frequency of the protons. For fast modulation frequencies, the modulation sidebands are well separated and might reach the working point of the proton machine. Fig.2 shows the transverse Q-diagram for a tune modulation with $f_{mod} = 1200Hz$ and $f_{rev} = 47.4KHz$. One clearly recognizes the additional modulation sidebands. In HERA, such a fast tune modulation is caused by ripples in the proton power supplies. In the quadrupole magnets the current ripple leads directly to a tune modulation, while in the dipole magnets the current ripple leads to a closed orbit oscillation. In combination with the beam-beam interaction and the resulting offset at the interaction region, the closed orbit oscillation leads to a tune modulation with a doubled frequency. Typical ripple frequencies are $50Hz$, $150Hz$, $300Hz$, $600Hz$ and $1200Hz$ and their harmonics. The resulting tune modulation depth is of the order of $\Delta Q \sim 10^{-4}$. Fig.2 shows the transverse Q-diagram for a tune modulation with $f_{mod} = 1200Hz$ and $f_{rev} = 47.4KHz$. With tune modulation, it is virtually impossible to find a working point in the transverse Q-diagram that is not close to a low order resonance. The

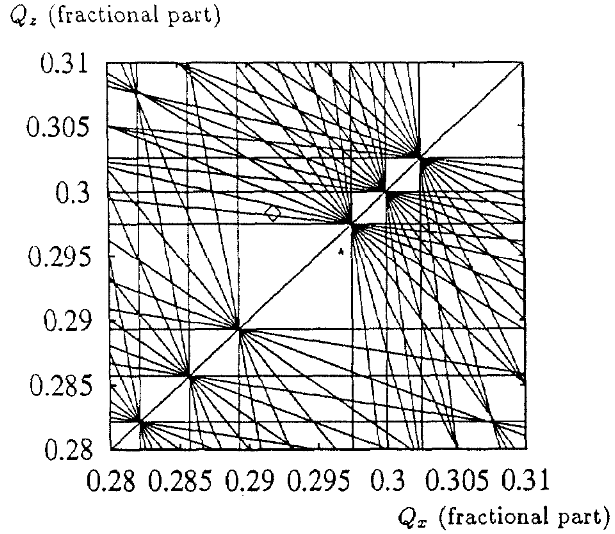

Figure 2: *The resonance lines and their first order sidebands ($n = \pm 1$) for a tune modulation with $1200Hz$.*

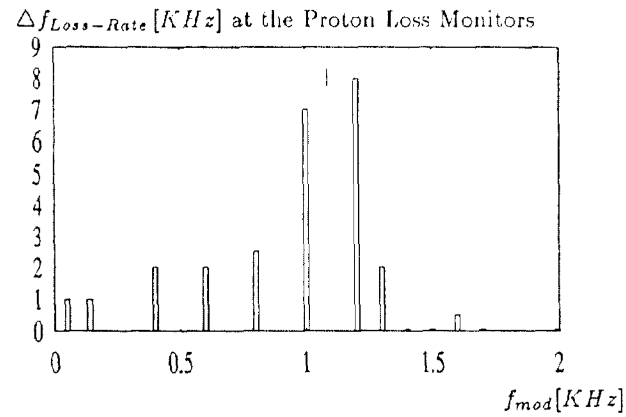

Figure 3: *Increase in the loss rate at the proton loss monitors for different modulation frequencies. For all modulation frequencies except for the $46.4Hz$, the modulation depth was $\Delta Q \sim 10^{-4}$.*

analysis in [1] showed that even for modulation depths as small as $\Delta Q = 10^{-4}$, the tune modulation leads to a significant particle diffusion once the modulation sidebands reach the particle distribution. Hence, one can conjecture that the tune modulation caused by the power supply ripples affects the beam lifetime and the background rates in the experiments.

2 EXCITATION OF AN ADDITIONAL TUNE MODULATION IN HERA-P

Because the spacing of the modulation sidebands in the Q-diagram depends only on the modulation frequency (see Equation (2)), one expects the particle diffusion to be highly sensitive to the modulation frequency. A subsequent diffusion experiment in the proton storage ring of HERA confirmed the frequency dependence of the particle diffusion and demonstrated that a tune modulation with amplitudes as low as $\Delta Q = 10^{-4}$ does indeed result in a substantially large particle diffusion [3]. Using four of the superconducting correction quadrupoles in the proton storage ring and a harmonic frequency generator, a harmonic tune modulation with $\Delta Q \approx 10^{-4}$ was created. During the experiment, the modulation frequency was varied in $100Hz$ steps between $2KHz$ and $400Hz$. The measured loss rates showed a distinct maximum for a tune modulation with $1.2KHz$ and confirmed the expected frequency dependence of the particle diffusion on the modulation frequencies. Fig.3 shows the difference between the measured proton loss rate with tune modulation and the loss rate without tune modulation for thirteen different modulation frequencies.

An analytical estimate for the diffusion coefficients yielded a maximum diffusion coefficient for a modulation frequency of $f_{mod} = 1.135KHz$ and agrees with the location of the measured maximum in Fig.3 [3]. During the experiment, the proton diffusion was inferred by scraping the beam with collimators and observing the subsequent increase in the proton loss rate [2][3]. The resulting diffusion coefficients also confirmed the expected maximum of the particle diffusion for a modulation frequency of $f_{mod} \approx 1.2KHz$ and showed that a tune modulation with modulation amplitudes as small as $\Delta Q = 10^{-4}$ leads to a drastic increase of the particle diffusion. For a tune modulation with a modulation frequency between $1200Hz$ and $400Hz$, the measured diffusion coefficient was approximately one order of magnitude larger than the measured diffusion coefficient for a tune modulation with any other modulation frequency.

3 COMPENSATION OF FAST MODULATION FREQUENCIES

Recognizing the damaging effect of the fast modulation frequencies on the long term stability of the stored protons, it is desirable to actively compensate for the modulation frequencies. A second diffusion experiment aimed to demonstrate that an external tune modulation can be used for a compensation of the fast frequencies components.

The prerequisite for the compensation of individual modulation frequencies is a device that allows the measurement of the existing modulation frequencies in the proton beam. A numerical simulation of the particle dynamics under the combined influence of the beam-beam interaction and tune modulation showed that the modulation frequencies also appear in the emittance growth rate. Thus, by looking at the frequency spectrum of the proton loss rate, one can identify the individual modulation frequencies [4]. The top picture in Fig.4 shows the power spectrum of the proton loss rate during a typical luminosity run in HERA up to $800Hz$. One clearly recognizes the typical $50Hz$, $150Hz$, $300Hz$, and $600Hz$ ripple frequencies of the proton power supplies and their harmonics.

Generating a tune modulation with the same amplitude as the observed modulation frequencies but with a 180^o phase difference and a constant phase relation with respect

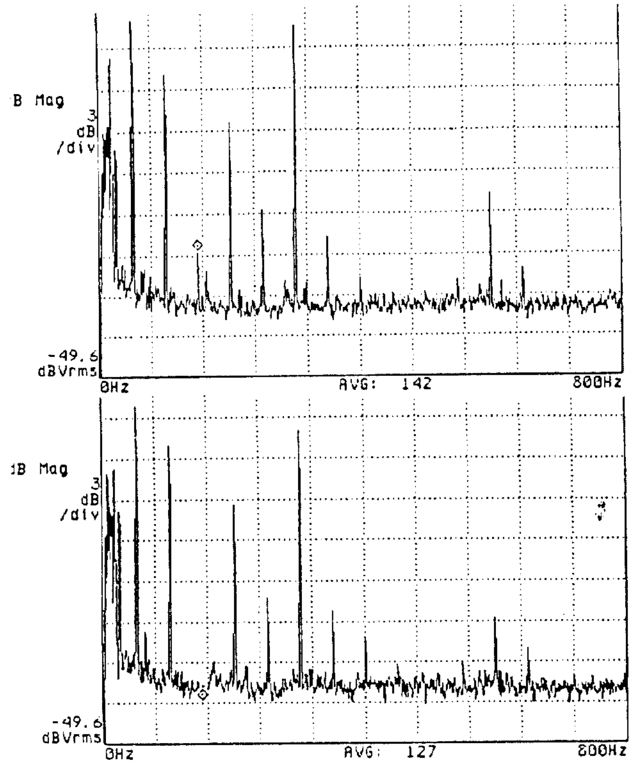

Figure 4: *The power spectrum of the proton loss rate. Top: The spectrum without an external tune modulation. Bottom: The spectrum with a 150Hz tune modulation and* $\Delta Q \sim 10^{-5}$

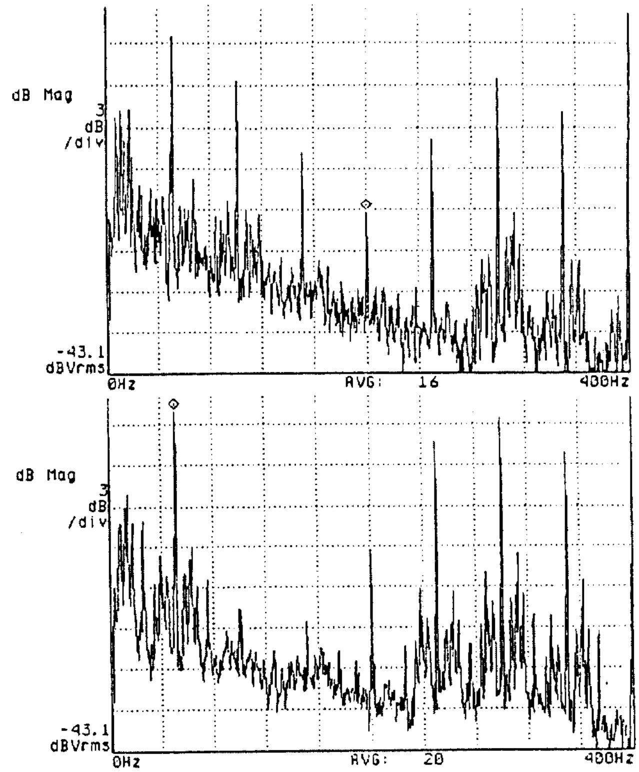

Figure 5: *The power spectrum of the proton loss rate. Top: The spectrum without an external tune modulation. Bottom: The spectrum with a 50Hz tune modulation and* $\Delta Q \sim 10^{-4}$.

to the power supplies, the external tune modulation was used successfully to compensate for individual frequencies in the Fourier spectrum of the proton loss rates. The bottom picture in Fig.4 shows the power spectrum for the same luminosity run as Fig.4, but with an external tune modulation with $150Hz$ and $\Delta Q = 10^{-5}$. The small square markes the $150Hz$ line and one clearly recognizes the disappearance of the $150Hz$ component.

Fig.5 illustrates that the external tune modulation can also be used to compensate for stronger signals and for more than one frequency component. The top picture in Fig.5 shows the power spectrum of the proton loss rate without an additional tune modulation up to $400Hz$. The bottom picture shows the spectrum with an additional tune modulation with $50Hz$ and $\Delta Q \sim 10^{-4}$. One clearly recognizes the disappearance of the $100Hz$ and $150Hz$ lines.

4 SUMMARY

The presented work briefly illustrated the effect of tune modulation on the phase space structure and summarized the main results of two diffusion experiments in the proton storage ring of HERA. In these experiments, superconducting correction quadrupoles in the proton storage ring were used to create an external tune modulation of the order of $\Delta Q \sim 10^{-4}$ with modulation frequencies between $40Hz$ and $2000Hz$. The first diffusion experiment confirmed the frequency dependence of the particle diffusion and demonstrated that a tune modulation with amplitudes as low as $\Delta Q = 10^{-4}$ results in a substantial particle diffusion during the luminosity operation. The second diffusion experiment showed that an external tune modulation can be used to compensate the natural tune modulation frequencies due to power supply ripples. The experiment was motivated by the idea that by compensating the modulation frequencies, the total loss rate could be reduced and the proton beam lifetime improved.

5 REFERENCES

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