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REDUCTION OF PROTON LOSSES IN HERA BY COMPENSATING THE TUNE MODULATION IN THE PROTON BEAM

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The combined effect of a tune modulation with more than one frequency component and the nonlinear fields due to the beam-beam interaction during luminosity operation leads to increased background rates and particle losses. The following work describes a new method of controlling the proton losses in HERA by compensating for fast modulation frequencies in the machine. The method allows a direct control of the particle diffusion in the beam halo without interfering with the normal luminosity operation. The work summarises experimental results of two experiments in the proton storage ring at DESY.

Keywords: Tune-modulation; loss-rate; diffusion; beam-beam.

1 INTRODUCTION

The beam-beam interaction is a source of strong non-linear fields in a collider. Thus, in order to achieve good lifetimes in a proton storage ring with colliding beams nonlinear resonances up to a high order must be avoided. In HERA, the working point of the proton beam is located near the main coupling resonance between the 7 th and 10 th order betatron resonance, where only resonance of 17^{th} order and higher are present. A typical proton working point in the 1994 luminosity operation was

$$Q_x = 31.294 \qquad \text{and} \qquad Q_y = 32.298. \tag{1}$$

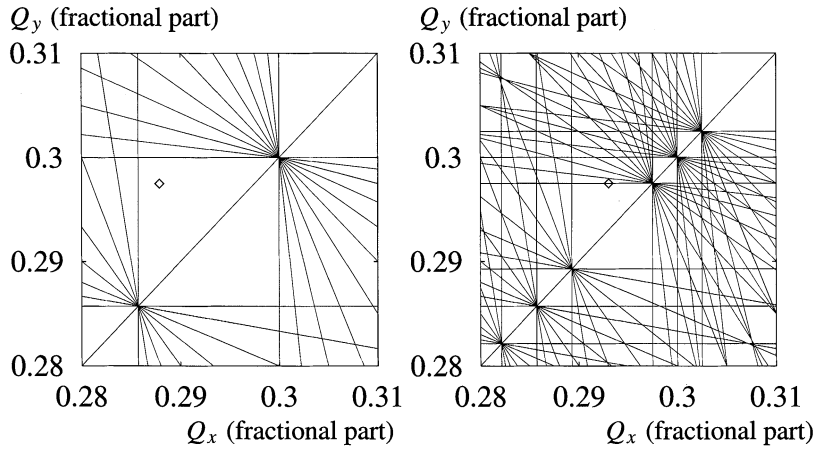

FIGURE 1 The working point of the proton beam in the tune diagram. The left-hand side shows the resonance lines up to 10 th order without tune modulation. The right-hand side shows the resonance lines up to 10 th order together with the first order modulation sidebands for a tune modulation with 1200 Hz.

The diamond shape in Figure 1 shows the working point in the transverse tune diagram. The left-hand side of Figure 1 shows the tune diagram without and the right-hand side with tune modulation. The tune diagram shows resonance lines up to 10 th order. Without tune modulation, the area between the 7 th and 10 th order resonances contains no low-order sum resonance lines. With tune modulation, modulation sidebands of the primary beam-beam resonances will be generated. For fast modulation frequencies ($f_{\mathrm{mod}} > 50$ Hz), the modulation sidebands might reach the working point of the proton beam even if it is placed well inside the resonance free area between the 7 th and 10 th order resonances. The right-hand side of Figure 1 shows the tune diagram for a tune modulation with 1200 Hz, where the modulation sidebands reach the working point of the proton beam. The tune spread of the proton beam is of the order of $\Delta Q = 10^{-3}$ in both planes during luminosity operation. Thus, a fast tune modulation drastically limits the available resonance free space in the tune diagram. Considering more than one fast modulation frequency and resonance lines up to 17 th order, it is virtually impossible to find a working point that is not close to a resonance sideband. In combination with an additional slow tune modulation ($f < 50$ Hz), the modulation sidebands overlap and give rise to modulational diffusion.[1] The analysis in Ref. 2 showed that for the design values of the HERA beam-beam parameters even modulation depths as small as $\triangle Q = 10^{-4}$ for the fast modulation frequencies and $\triangle Q = 10^{-5}$ for the slow modulation frequencies result in a significant particle diffusion and thus particle loss once the modulation sidebands reach the particle tune. This result was confirmed by experimental data taken at HERA where an additional tune modulation with $\triangle Q \approx 10^{-4}$ was applied at different frequencies. Figure 1 suggests that for a given working point, the proton losses due to modulation sidebands depend on the modulation frequency. If the modulation sidebands do not fall onto the working point of the proton beam, the change in the loss rates will be small and if the modulation sidebands fall right on the proton working point, the change in the loss rates will be large. This dependence of the loss rates on the modulation frequency was confirmed by the experimental data in Ref. 3. During the experiment, the modulation frequency was varied in 100 Hz steps between 2 KHz and 400 Hz. The measured loss rates showed a distinct maximum for a modulation frequency of 1.2 KHz and confirmed the expected frequency dependence of the particle diffusion on the modulation frequencies. Figure 2 shows the difference between the measured proton loss rate with tune modulation and the loss rate without tune modulation for thirteen different modulation frequencies. During the experiment, the diffusion coefficient was estimated by scraping part of the beam halo with a collimator and retracting the collimator afterwards by typically 0.2 mm. The diffusion coefficient in the beam halo was then estimated by fitting the solution of the diffusion equation with the appropriate boundary conditions to the time evolution of the loss rates.[4] The analytical estimate for the diffusion coefficients yielded a maximum diffusion coefficient for a modulation frequency of $f_{\mathrm{mod}} = 1.135$ KHz. The measurement yielded a maximum diffusion coefficient for a modulation frequency of 1.1 KHz and confirmed the analytical result. The measured diffusion coefficient agreed within an order of magnitude with the analytical estimates and was approximately two orders of magnitude larger than the measured coefficients without any additional tune modulation.

2 COMPENSATION OF FAST MODULATION FREQUENCIES

In the proton storage ring of HERA, a fast harmonic tune modulation is caused by ripples in the power supplies. Typical ripple frequencies are 50 Hz, 150 Hz, 300 Hz, 600 Hz and 1200 Hz and their harmonics and the resulting tune

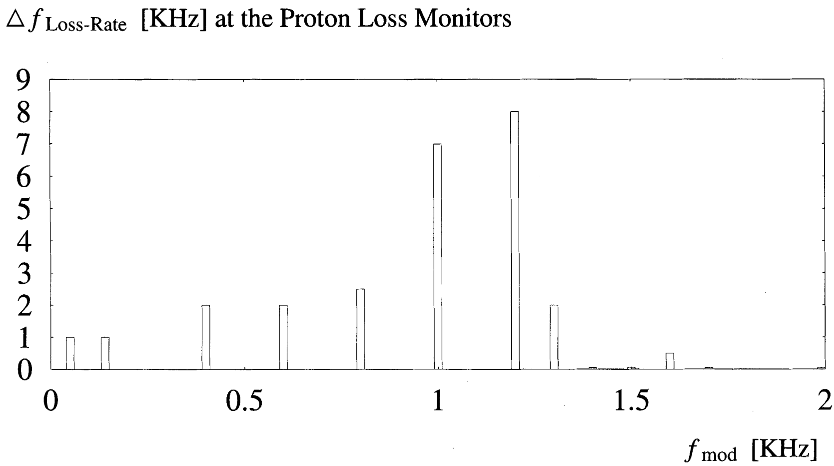

FIGURE 2 Increase in the loss rate at the proton loss monitors for different modulation frequencies. For all modulation frequencies except for the 46.4 Hz, the modulation depth was $\triangle Q \sim 10^{-4}$.

modulation depths is of the order of $\triangle Q \sim 10^{-4}$. A slow tune modulation between 1 Hz and 20 Hz is caused by the ground motion in the HERA tunnel. Typical modulation depths are $\triangle Q \approx 10^{-5}$. Furthermore, the synchrotron oscillation in the proton beam and vibrations of the vacuum pumps lead to an additional tune modulation at 30 Hz and 24 Hz and 48 Hz with modulation depth of $\triangle Q \approx 10^{-5}$. Recognising the damaging effect of a fast tune modulation due to power supply ripples, it is desirable to minimise either the ripple amplitudes at the power supplies or to actively compensate for the tune modulation in the storage ring by generating an additional external tune modulation with the same frequency spectrum as the tune modulation due to power supply ripples but with an 180° phase difference. In the following, we will follow the second approach.

The prerequisites for a tune ripple feed-back system are a method to excite an additional tune modulation with a constant phase relationship with respect to the power supplies in a way that does not interfere with the normal operation of the machine and a monitor that allows the measurement of modulation depths of the order of $\triangle Q \approx 10^{-5}$. In HERA, an external tune modulation can be generated by modulating the current in the superconducting correction quadrupoles. This approach requires only a small modification of the electronics of the chopper-type power supplies and allows a modulation of regular quadrupole magnets in the lattice. In order to achieve a constant phase relationship of the generated signal and the power supply ripples, the modulation signal is triggered by a 50 Hz signal from the power supplies. Using a phase-locked-loop (PLL) for monitoring the modulation frequencies and amplitudes in the beam, one can adjust the additional tune modulation so that the modulation amplitudes in the beam attain a minimum. Figure 3 shows the schematic layout of the experimental set up. The PLL consists of a transverse kicker and pickup in the storage ring a phase discriminator and a voltage controlled oscillator (VCO). The signal from the beam pickup drives the frequency of the VCO and the signal from the VCO is connected to a transverse kicker. The PLL constantly measures the betatron frequency, adjusts the VCO frequency according to the measurement and excites the beam on the VCO frequency. Once the PLL locked on to the betatron frequency, the control voltage of the VCO will follow any changes in the proton betatron frequency. Thus, a Fourier analysis of the change in the control voltage of the VCO is a measure of the existing tune modulation in the storage ring. The left-hand side of Figure 4 shows the spectrum of the vertical PLL without an additional external tune modulation. In order to compensate a frequency component in the spectrum, for example the 600 Hz component, the frequency line is first calibrated by generating an additional harmonic tune modulation with a slightly different frequency and given amplitude. The calibration should be done with a frequency that does not appear in the natural PLL spectrum. During the HERA experiments, the calibration frequency was typically chosen 20 Hz larger than the selected frequency in the PLL spectrum. Once the modulation amplitudes of the frequency lines in the PLL spectrum are known, a compensation of the frequency lines can be achieved by generating an additional harmonic tune modulation with the same frequency and amplitude and varying the phase of the generated signal until the frequency line attains a minimum in the PLL spectrum. The right hand-side of Figure 4 shows the corresponding PLL spectrum for a successful compensation of the 600 Hz line in the PLL spectrum. During the HERA experiments, the compensation was done using one super-conducting quadrupole correction family for each plane. Both quadrupole families extend over one quadrant of the storage ring. The modified chopper power supplies yield a maximum modulation amplitude of ± 35 V per quadrupole family. For tune ripple amplitudes of the order of $\Delta Q = 10^{-4}$, the current maximum available modulation voltage limits the compensation to only one or two frequency lines per plane.

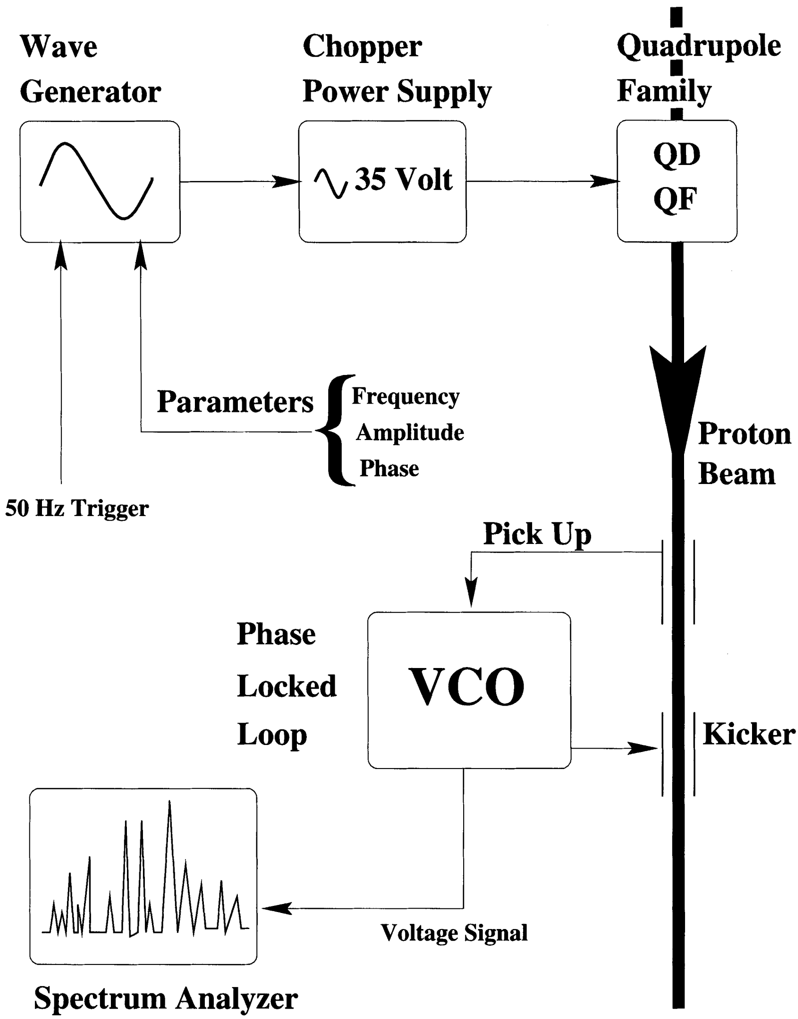

FIGURE 3 Schematic setup of the compensation scheme.

However, by using the correction quadrupoles in all four arcs the compensation can be extended to up to 4 to 8 frequency lines per plane. Due to the inductivity of the quadrupole chains and the frequency dependent screening of the magnetic fields by the 10 μm thick copper layer inside

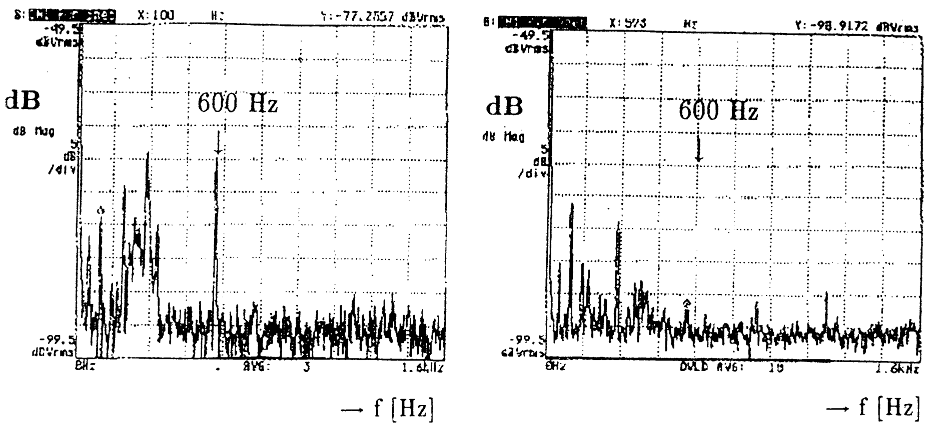

FIGURE 4 The vertical phase-locked-loop spectrum at 820 GeV. The picture shows the spectrum between 0 Hz to 1.6 KHz.
Left: without an additional external tune modulation.
Right: with an additional tune modulation compensates the 600 Hz line.

the vacuum chamber, the maximum modulation amplitude decreases with increasing modulation frequency. For example, for a modulation frequency of 600 Hz the maximum modulation voltage corresponds to a maximum tune modulation of $\triangle Q_{\max} \approx 1 \cdot 10^{-4}$ and for a modulation frequency of 300 Hz to $\triangle Q_{\max} \approx 3 \cdot 10^{-4}$.

3 EXPERIMENTAL RESULTS

Figure 5 shows three different situations in the compensation process: Part 1, from 5.87 hours to 5.96 hours, shows the loss rate during the calibration of the 300 Hz line in the PLL spectrum with an additional tune modulation of 320 Hz. As the amplitude of the 320 Hz signal increases, the loss rate also increases. Once the amplitude of the 300 Hz line is calibrated, the amplitude of the 320 Hz signal is set to zero and the loss rate attains again its initial value of 1700 Hz at 5.88 hours. The frequency of the external signal is now set to 300 Hz and the phase of the signal with respect to the 50 Hz trigger signal of the power supplies is adjusted. First, the loss rate increases again once the external modulation is turned on and then slowly decreases with the changing phase of the external signal. The loss rate attains a minimum of 1400 Hz

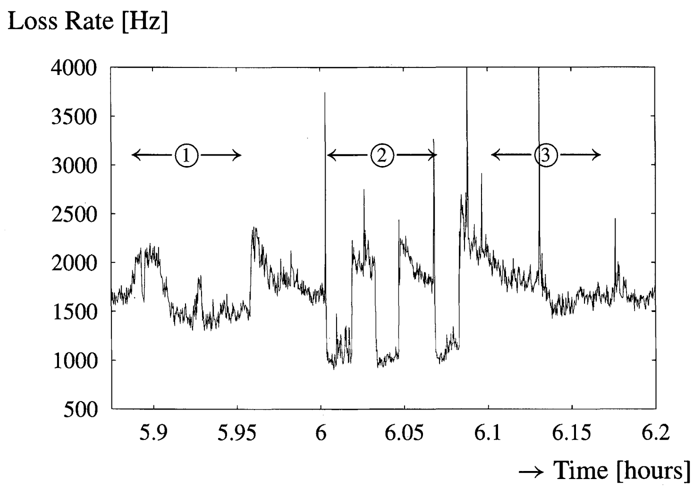

FIGURE 5 The proton loss rate at the main collimator jaw during the compensation procedure versus time.

at 5.925 hours when the 300 Hz line in the PLL spectrum is compensated and increases again once the phase is further increased. At 5.93 hours the phase is set back to its optimum value and the loss rate attains again its minimum value of 1400 Hz. At 5.96 hours, the external modulation is turned off and the loss rate goes up again to its initial value of 1700 Hz. In the second part, from 6.0 hours to 6.08 hours, a compensation of the horizontal 100 Hz and 300 Hz and the vertical 100 Hz line is turned on. The loss rate drops from 1700 Hz to 900 Hz. The compensation is then repeatedly turned on and off and the loss rate changes from approximately 1700 Hz without compensation to 900 Hz with the compensation on. In all cases, the compensation results in a reduction of the loss rate of approximately 40%. In the third part, from 6.08 hours to 6.2 hours, the compensation is turned off and the loss rate increases and assymtotically reaches again its initial value of 1700 Hz.

The increase of the loss rate to values larger than the initial rate of 1.7 KHz without any additional tune modulation can be explained by an accumulation of particles near the collimator jaw. During the compensation, the particle diffusion in the beam halo is smaller than without the compensation and fewer particles are lost. Because of the strong amplitude dependence of the beam-beam resonances, the diffusion due to the modulation sidebands mainly affects the particles in the beam halo and does not affect the particle flow from the beam core to the beam halo. Thus, as the particle density at the collimator is determined by the number of particles coming from the beam core and the number of particles lost at the collimator, a reduction of the particle diffusion mainly at larger amplitudes leads to a higher particle density in the beam halo. If the compensation is turned off again, the particle diffusion attains again its initial value and the increased number of particles in the beam halo leads to a large initial increase in the loss rate until the particle distribution attains again a steady state.

In all cases, the compensation of frequency lines in the PLL spectrum leads to a reduction of the loss rate. Once the compensation is turned off, the loss rate increases again to its initial value of approximately 1.7 KHz. For a compensation of the horizontal 100 Hz and 300 Hz and the vertical 100 Hz lines, a reduction of up to 40% could be achieved. In all cases, the final reduction of the loss rate depends on the chosen modulation frequencies and the number of compensated frequency lines. In general, the reduction was better when more frequency lines were compensated. Thus, one can expect to achieve a reduction in the loss rate of more than 40% once one can compensate for more than three frequency lines.

In all cases the emittance growth due to the PLL excitation was monitored. Once the PLL locked on to the betatron frequency, the excitation amplitude in the kicker can be reduced to small values so that the excitation does not significantly dilute the beam emittance. In HERA, the PLL was continuously operated for one hour without measuring a noticeable effect on the transverse beam size. Furthermore, amplitude and phase of the original ripples turned out to be quite stable during a luminosity run. Once the parameters for the compensation have been determined at the beginning of a run, they need not to be changed during a luminosity run. Therefore the PLL does not have to run during the whole time avoiding any detrimental side effects on the proton beam this way.

4 SUMMARY

The presented work demonstrates how an external tune modulation can be used to compensate for a tune modulation due to power supply ripples. First experiments in the proton storage ring of HERA showed that a compensation of the fast frequency components results in a substantial reduction of the proton loss rate during luminosity operation and led to the development of an 'tune modulation feedback system' in HERA. The reduction in the loss rate is the better, the more frequency lines are compensated. During the experiments in HERA, only three frequency lines of a total of approximately 10 dominant lines could be compensated simultaneously. The limitation to only three frequency lines is given by the maximum available modulation amplitude according to the available voltage of the used power supply. This is no principal limitation since there are still three equivalent circuits available in HERA which can be used for the compensation of more ripple frequencies. The 'tune modulation feedback system' is now ready to go and has been tested in the 1995 machine study period of HERA. The presented results illustrate the effect of tune modulation on beam losses during luminosity operation and demonstrate the feasibility of a 'tune modulation feedback system', which can drastically reduce the tune modulation due to power supply ripples. The compensation of only three frequency lines with modulation depth of the order of $\triangle Q \approx 10^{-4}$ in the tune modulation spectrum of HERA-p, lead to a reduction of the proton loss rate by almost 40%.

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