REDUCTION OF PARTICLE LOSSES IN HERA BY GENERATING AN ADDITIONAL HARMONIC TUNE MODULATION

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Abstract

The combined effect of non-linear fields and a tune modulation with fast and slow frequency components results in an enhanced emittance growth and increased loss rate in hadron storage rings. 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. The recognition of the damaging effect of fast tune modulation frequencies on the particle dynamics initiated attempts to compensate for the fast frequency components in HERA. The fast tune modulation frequencies in the proton beam can be measured with a phase-locked-loop and the compensation can be established by generating an additional external tune modulation with the same frequency but with a 180^o phase difference. The following work summarizes the results of recent experiments in the proton storage ring of HERA where the generation of an additional tune modulation led to a significant reduction of the proton loss rate during luminosity operation.

I. INTRODUCTION

During luminosity operation, the beam-beam interaction in the lepton-hadron collider HERA is a source of strong non-linear fields. An additional tune modulation leads to resonance sidebands of the primary beam-beam resonances. For slow modulation frequencies ($f < 50Hz$), the modulation sidebands overlap and give rise to modulational diffusion [1]. For the beam-beam interaction in HERA, the modulational diffusion primarily affects the particles in the beam halo and results in particle loss and increased background rates in the experiments [2]. In order to avoid a modulational diffusion with strong resonances, the working point of the proton beam in HERA is located between the $7th$ and $10th$ order betatron resonance. Without tune modulation, the area between the 7^{th} and 10^{th} order resonances contains no low-order sum resonance lines [2]. Thus, one expects a sufficiently large beam lifetime for any working point between the 7^{th} and 10^{th} order resonances.

For fast modulation frequencies ($f > 50Hz$), the modulation sidebands do not overlap, but might reach the working point of the proton beam even if it is well inside the resonance free area between the 7^{th} and 10^{th} order resonances. The combined influence of such fast modulation sidebands and an additional slow tune modulation results again in modulation diffusion [2]. Thus, with slow and fast modulation frequencies it is virtually impossible to find a working point that does not lie near a non-linear resonance sideband. In HERA, a slow tune modulation is caused by the ground motion in the HERA tunnel and by the longitudinal synchrotron oscillation ($f_{syn.} \approx 30Hz$). The frequency spectrum of the ground motion reaches from $1Hz$ to $20Hz$ with modulation depths of the order of $\triangle Q \sim 10^{-5}$. A fast tune modulation is caused by ripples in the proton power supplies in HERA. All the superconducting main magnets of the HERA-p storage ring are connected in series. The current flows first clockwise from the power supply in Halle West through all the main dipole magnets and then counter-clockwise through all the main quadrupole magnets back to the power supplies. Thus, the first magnets of both chains see the same voltage ripples. Typical ripple frequencies are $50Hz$, $150Hz$, $300Hz$, $600Hz$ and $1200Hz$ and their harmonics and the resulting tune modulation depth is of the order of $\triangle Q \sim 10^{-4}$. The analysis in [2] showed that for the design values of the HERA beam-beam parameters even modulation depths as small as $\triangle Q = 10^{-4}$ result in a significant particle diffusion once the modulation sidebands reach the particle tune. Because the particle dynamics in hadron storage rings has virtually no damping, the resulting diffusion can spoil the long-term stability of the particles and might result in large loss rates [2]. A subsequent experiment in the proton storage ring of HERA confirmed this expectation [3].

II. COMPENSATION OF FAST MODULATION FREQUENCIES

Recognizing the damaging effect of a fast tune modulation due to power supply ripples, it is desirable to minimize 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^o phase difference. The first approach requires active filters for each power supply and is technically difficult and expensive. On the other hand, the second approach, a compensation of existing modulation frequencies by actively generating an additional tune modulation in the storage ring, requires only minor changes in the existing hardware and presents an interesting new method for improving the quality of the power supplies and improving the beam performance.

In HERA, an external tune modulation can be generated by modulating the current in two superconducting correction quadrupole families. This approach requires only a small modification of the chopper electronics in the proton 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 $50Hz$ signal from the power supplies.

The prerequisite for a compensation of the tune modulation due to power supply ripples is a monitor that allows the measurement of the existing tune modulation frequencies in the storage ring. In HERA, first attempts of a tune modulation compensa-

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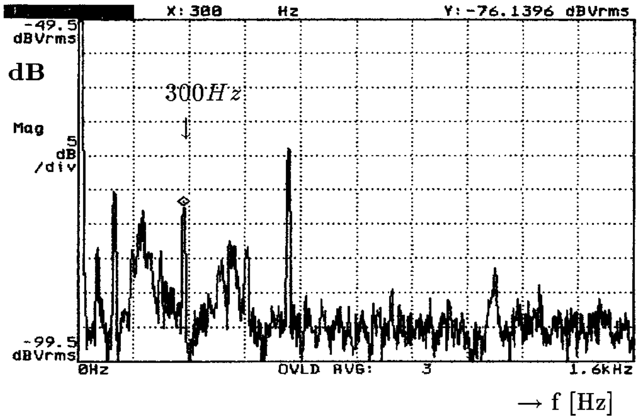

Figure 1. The horizontal phase-locked-loop spectrum at $820GeV$ without and additional external tune modulation.

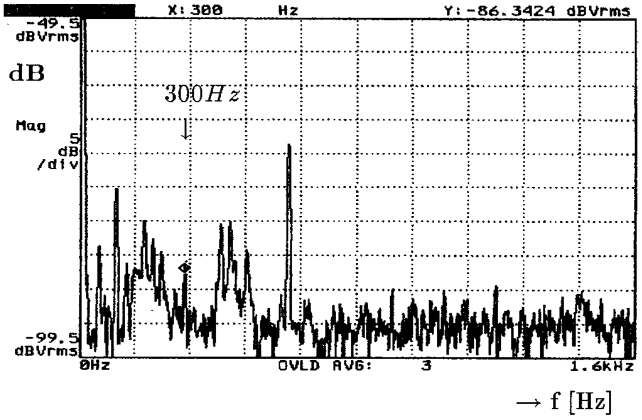

Figure 2. The horizontal phase-locked-loop spectrum at $820GeV$ with an additional tune modulation of $300Hz$ and $triangleQ \approx 10^{-4}$. The additional tune modulation compensates the $300Hz$ line of the original phase-locked-loop spectrum.

tion were made using the loss spectrum at the proton collimators as a monitor for the modulation frequencies in the storage ring [4]. However, even though it is possible to compensate individual frequency lines in the loss spectrum, the compensation does not result in a reduction of the total loss rate [4]. On the contrary, the compensation results in increased loss rates. The increase in the loss rate can be related to three characteristic aspects of the proton loss spectrum: First, the loss spectrum does not allow a distinction between modulation frequencies in the horizontal and vertical plane; Second, the loss spectrum does not allow a distinction between tune modulation, closed orbit motion, and beta-beats; and third, even a tune modulation with only one frequency component results in a whole spectrum of frequency lines in the loss spectrum [5]. Thus, the proton loss spectrum does not allow a reliable measurement of the existing tune modulation frequencies in the storage ring and can not be used as a monitor for the existing tune modulation in the storage ring.

However, the first compensation attempts with the proton loss spectrum illustrated two important aspects of the tune modulation in HERA and motivated further studies. First, the first experiments showed that a tune modulation with amplitudes as small as $\triangle Q \sim 10^{-4}$ does influence the proton loss rate as it is expected from the analytical analysis. And second, the results showed that the fast modulation frequencies in the loss spectrum are phase synchronous with the power supplies.

III. MEASURING THE TUNE MODULATION WITH A PHASE-LOCKED-LOOP

A new approach is to use a phase-locked-loop (PLL) for the measurement of the existing tune modulation in the storage ring. This results in a successful compensation of the individual frequency lines in the PLL spectrum and a substantial reduction in the total proton loss rate. In contrast to the proton loss spectrum, the spectrum of the PLL is neither sensitive to closed orbit motion nor to a modulation of the beam size. Furthermore, each tune modulation frequency leads to one unique frequency line in the PLL spectrum. The PLL consists of a transverse kicker and pickup in the storage ring 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 the 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 excitation amplitude in the kicker can be reduced to small values so that the excitation does not significantly dilute the beam profile. In HERA, the PLL was operated for one hour without measuring a noticeable effect on the transverse beam size.

The difference between the measured betatron frequency and the current oscillation frequency of the VCO provides a sensitive measurement of the fluctuations in the mean betatron frequency. Thus, a Fourier analysis of the difference signal is a measure of the existing tune modulation of the storage ring. Fig.1 shows the spectrum of the horizontal PLL without an additional external tune modulation. In order to compensate a frequency component in the spectrum the frequency line is first calibrated by generating an additional harmonic tune modulation with given amplitude. 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. Fig.2 shows the corresponding PLL spectrum of Fig.1 for a successful compensation of the $300Hz$ line in the PLL spectrum.

IV. EXPERIMENTAL RESULTS

Fig.3 shows the proton loss rate at the main collimator during the compensation procedure as a function of time. The picture 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 $300Hz$ line in the PLL spectrum with an additional tune modulation of $320Hz$. As the amplitude of the $320Hz$ signal increases, the loss rate also increases. Once the amplitude of the $300Hz$ line is calibrated, the amplitude of the $320Hz$ signal is set to zero and the loss rate attains again its initial value of $1600Hz$ at 5.88 hours. The frequency of the external signal is now set to $300Hz$ and the phase of the

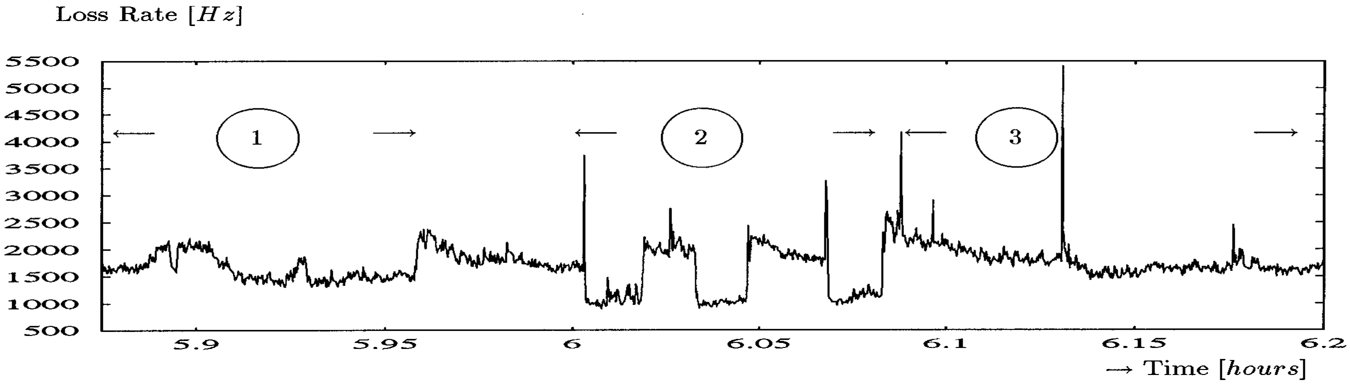

Figure 3. The proton loss rate at the main collimator jaw during the compensation procedure.

signal with respect to the $50Hz$ 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 $1400Hz$ at 5.925 hours when the $300Hz$ 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 $1400Hz$. At 5.96 hours, the external modulation is turned off and the loss rate goes up again to its initial value of $1600Hz$.

In the second part, from 6.0 hours to 6.08 hours, a compensation of the horizontal $100Hz$ and $300Hz$ and the vertical $100Hz$ line is turned on and the loss rate drops from $1600Hz$ to $900Hz$. The compensation is then repeatedly turned on and off and the loss rate changes from approximately $1600Hz$ without compensation to $900Hz$ 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 $1600Hz$.

V. SUMMARY

The presented work illustrates how the tune modulation due to power supply ripples can be compensated by generating an additional external tune modulation. 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. The reduction in the loss rate is the better, the more frequency lines are compensated. So far, 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 for the external signal and an increase of the total modulation amplitude is expected to allow an even better reduction of the proton loss rate.

By compensating only three frequency lines in the tune modulation spectrum of HERA-p, the proton loss rate could be reduced by almost 40%. This encouraging result led to the construction of a 'tune modulation feedback system', which is now ready to go and will be tested in the 1995 luminosity operation of HERA.

References

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