Measurement Setup for Bunched Beam Echoes in the HERA Proton Storage Ring

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Abstract

Echo experiments are one of the most powerful tools for the determination of diffuse processes in many body systems. Within the scope of beam dynamics experiments for examination of the longitudinal behavior of the bunched HERA proton beam, we started to establish beam echo measurements. These first required some tests on the RF system to provide sufficiently short and powerful RF kicks. For the detection of the beam response we used the real time single shot bunch phase and length measurement [1] with a modified timing scheme. From these measurements we were able to determine the values for the Landau damping times at 40 GeV and at 920 GeV in HERA for the first time. Furthermore the measured data showed a clear relation between the elapsed time between the dipole and the quadruple kick and the echo strength. So far measurements with controllable RF noise have not resulted in a uniform response of the echo amplitude.

1 INTRODUCTION

Normally, in microscopic many body systems of identical particles, one cannot stimulate and measure an individual particle. On the contrary one always stimulates and measures an ensemble. Provided the behavior of the particles is slightly different, because of varying surroundings, the response of the ensemble is influenced by this difference. The measurement of the ensemble compared to the measurement of a single particle can differ extremely. Echo experiments are methods to eliminate the different behavior of the particles. These techniques exist in plasma physics, have become very sophisticated in solid states physics, and have been recently used in proton accelerator physics [2, 3, 4].

In the case of a proton bunch we have the following situation: A sufficiently short kick on the RF phase e.g. a quarter of the synchrotron oscillation period, causes a phase oscillation. Shortly after the kick all protons oscillate in phase and as a result the bunch center oscillates. The synchrotron frequency of a single proton depends on its maximum oscillation amplitude because of the flatter bucket potential at higher oscillation amplitudes. The larger the maximum amplitude is the lower is the synchrotron frequency. Because of this dependence the kicked protons lose their phase relation after a certain time and the bunch center oscillation decays. This damping of the bunch center oscillation is called Landau damping.

The single proton still oscillates and carries the information about the phase kick. From an RF amplitude kick it is possible to reconstruct a part of the initial phase dependence of the protons and thus obtain a bunch center oscillation. This is called the echo.

Some of the single protons loose information about the phase kick by scattering processes. When there is a long time between the phase kick and the amplitude kick, more information is lost. This influences the reconstruction, i.e. the echo will become smaller.

This method only makes sense, when the Landau damping time is smaller than the time constant of the scattering processes. However this is normally true in a proton accelerator.

One can develop bunch shape oscillations in a series of modes. The first mode is a bunch center oscillation called the dipole mode and the second one a bunch length oscillation called the quadrupole mode. Thus we refer to the RF phase kick as a dipole kick, because the dipole mode is excited, and to the RF amplitude kick as a quadrupole kick.

2 RF KICK PRODUCTION

At injection energies of the HERA proton storage ring at 40 GeV the RF buckets are mainly built up by the two 52 MHz RF cavities. So it is most effective to produce the necessary RF kicks by modulating the RF of one of the 52 MHz cavities. During acceleration to 920 GeV the RF amplitude of the 208 MHz cavities is increased such that at 920 GeV these systems mainly build up the RF buckets. In this case the RF kicks must therefore be produced by an intervention into the RF control loops of one 208 MHz cavity.

The technical assembly of both RF systems is different, this requires two different techniques for the RF kick production. To determine the particular solution, some tests and small modifications to the RF system were necessary. These changes were not inside the control loops but rather at connection points between the control system front end computers (FECs) and the analog control loops. We observed no negative influences on normal operation of the storage ring caused by these modifications.

To generate two rectangular signals with programmable amplitude, width, and time separation between them, we used the four channel digital delay / pulse generator from Stanford Research System model DG535. We controlled it via a GBIB connection to a UNIX workstation. This generator also provided a trigger signal to the real time single shot beam diagnostic. Because we are just starting to establish beam echo measurements in HERA the control software for the kick production with the Stanford DG535 and the control software for the single shot beam diagnostic were implemented on two different computer platforms. Thus the recording time of the measurement series was dominated by the time of oral communication.

2.1 52 MHz RF-System

The 52 MHz RF system provides a feed forward compensation input for an additional RF signal to compensate beam loading. Since HERA started running in 1992, this input has never been used. In order to enable this signal path, one had to set the corresponding property in the low level control system available in the proton RF control electronic room.

After doing this one can add any RF signal to the RF control signal which drives the final stage amplifier for the cavity. We used two 52 MHz RF bursts produced with an I/Q modulator. For the local oscillator, LO signal we took the 52 MHz RF reference. By supplying the I/Q modulator at the I input with the first rectangular signal from the Stanford DG535 and the Q input with the second one we produced two RF bursts with a phase relation of 90°. The observation of the cavity voltage by sampling the output signals of an I/Q demodulator indicated the necessary adjustment of the cable length and therewith the phase between RF control signal and the added RF bursts. We chose the cable length so that the first burst produced a dipole kick and the second one a quadrupole kick. For the technical setup see figure 1.

Amplitude and Phase are set at the 52 MHz RF system via an open loop control. Therefore the kicks produced by using the feed forward compensation input are not suppressed by a control loop.

Figure 2 shows the real and imaginary part of the angular pointer of the 52 MHz Cavity No 1 taken by I/Q demodulation of the diagnostic pickup signal. Note that the two RF bursts act relatively cleanly as pure phase and amplitude kicks.

2.2 208 MHz RF-System

The first idea was to produce the RF kicks at the 208 MHz RF system in the same way as at the 52 MHz system i.e. via the feed forward compensation input, which is not yet used. In contrast to the 52 MHz system an amplitude and phase

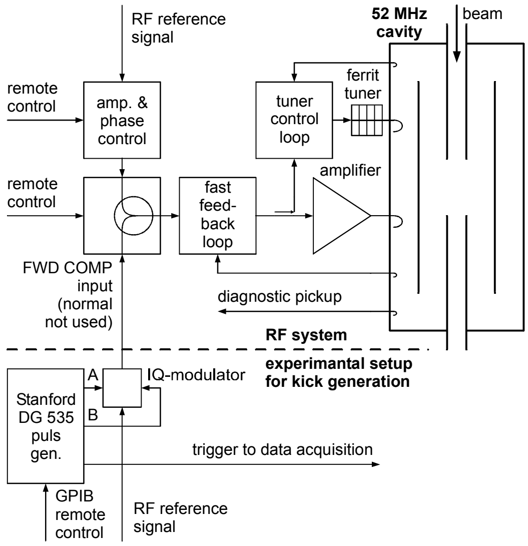

Figure 1: The 52 MHz RF System for a accelerating cavity and the intervention for the RF kick production.

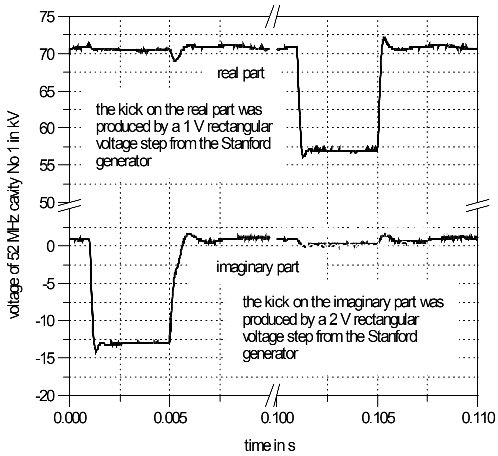

Figure 2: The I/Q demodulated 52 MHz pickup signal shows a dipole kick followed by a quadrupole kick.

closed loop control is implemented. It turned out that this control loop has a time constant shorter than the necessary kick duration of about 4 ms. This means that it suppresses kicks produced by adding RF bursts via the feed forward compensation input.

A way out of this dilemma was a change of the set points, "amp." and Φ of the amplitude and phase regulation loop [5], see figure 3.

The philosophy for normal operation of the storage ring is to change the RF values only adiabaticly. For this reason the input for the phase at the loop was provided with a low pass filter realized with a capacitor. For the kick production we had to remove this capacitor. Under normal conditions the phase value set from the control system for a single 208

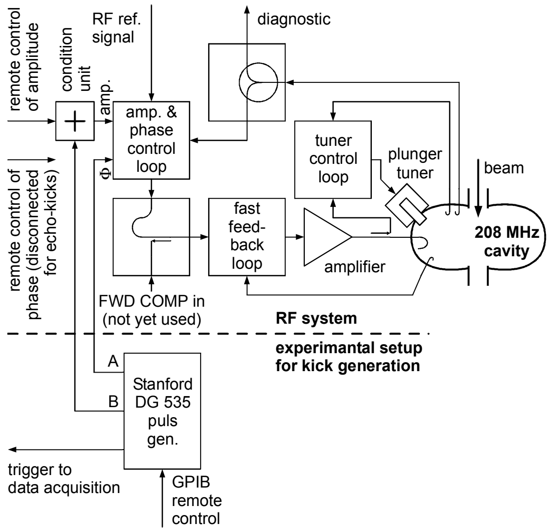

Figure 3: 208 MHz RF system of one cavity and the setup for the kick production.

MHz cavity is zero during the whole operation. So it was possible to unplug the control system at this point and plug in the Stanford DG535 signal for the dipole kick.

One is able to add an amplitude modulation to the amplitude set point chosen via the control system at the condition unit. This unit followed the same philosophy e.g. only adiabatic changes were used. Therefore a capacitor used for low pass filtering was also removed. Finally we were able to supply kicks with sufficient rise times and power see figure 4.

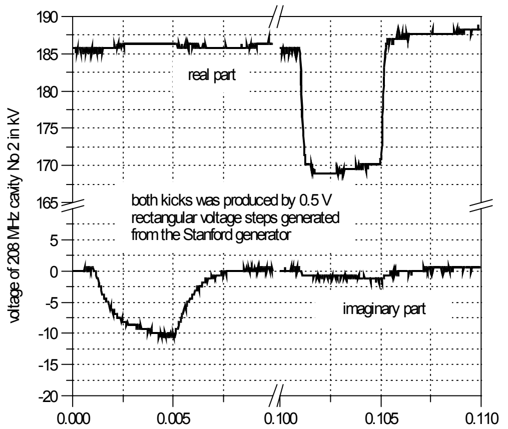

Figure 4: I/Q demodulated 208 MHz pickup signal with dipole kick followed by a quadrupole kick.

3 MEASUREMENT OF BEAM PROPERTIES

The reader can find a detailed description of the real time single shot bunch phase and length measurement at HERA in [1]. Here we will only give a sketch of the principles used.

3.1 Single Bunch Phase and Length

A bunch passing a resistive gap monitor leads to a broadband RF pulse whose shape is identical with the longitudinal bunch shape. This signal is analyzed by analog signal processing, see figure 5.

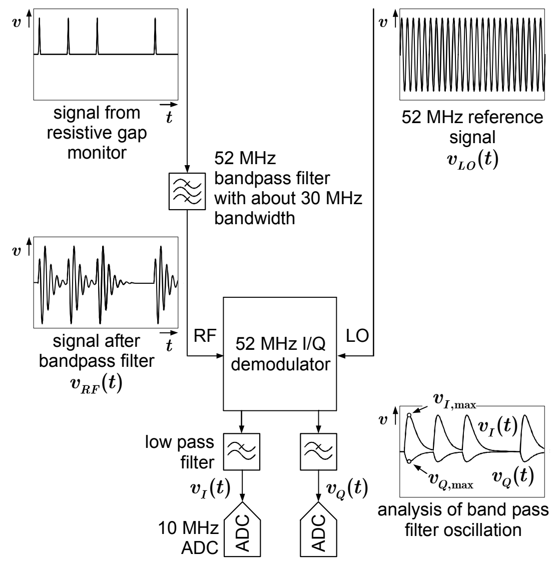

Figure 5: Principle of bunch phase measurement with a special designed 52 MHz band pass filter.

With this bunch signal one excites an oscillation in a 52 MHz band pass filter, whose properties are chosen so that the oscillation stops when the signal from the next bunch arrives. This oscillation is down-converted by an I/Q demodulator to the real and imaginary part from the angular pointer of this oscillation. By sampling these real and imaginary parts at the maximum value of the pointer length one gets, via the arctangent, the bunch phase $\Delta\phi$ and, via the absolute value, the 52 MHz bunch Fourier coefficient A_{52}

$$
\begin{aligned}
\Delta\phi &= \arctan\frac{v_{Q,\max}}{v_{I,\max}} + \Delta\phi_{cal} \\
A_{52,meas} &\equiv \sqrt{(v_{I,\max})^2 + (v_{Q,\max})^2} \\
A_{52} &= A_{52\,,cal}\, A_{52,meas}.
\end{aligned}
$$

$\Delta\phi_{cal}$ and $A_{52\,,cal}$ are calibration constants.

Assuming a Gaussian bunch shape, one can calculate the bunch length from the Fourier coefficients A_1 and A_2

for two different frequencies ω_1 and ω_2 of the longitudinal bunch shape

$$l_{FWHM} = 2\sqrt{\ln 4}\sqrt{\frac{2}{\omega_2^2 - \omega_1^2}}\sqrt{\ln\frac{A_1}{A_2}}\ \mathrm{c}.$$

The coefficient A_1 of the first frequency, 52 MHz, is delivered by the assembly of the phase measurement. For the determination of A_2 the direct measurement of the 208 MHz bunch Fourier coefficient with a 208 MHz band pass filter and an RF diode is used, see figure 6.

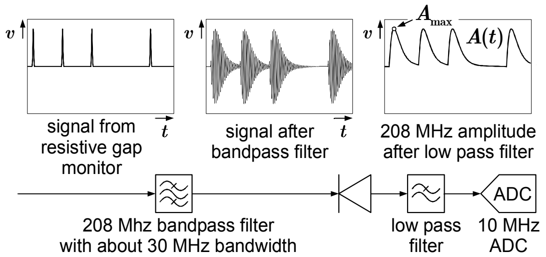

Figure 6: Princple of 208 MHz bunch Fourier coefficient measurement calculating back the bunch length.

3.2 Timing

In contrast to the measurement of multi-bunch oscillations in [1] we here measured only one bunch. This leads to a good flexibility at the observation times because of the relatively high amount of ADC memory available. For example we were able to observe the synchrotron oscillations of the bunch over a time of about 72 s without any gap. By reducing the observation time we can increase the time resolution.

To measure the bunch phase and length at a certain time, we first sampled the signals in the dump gap and directly afterwards we measured for the first bunch the signals from the phase and the 208 MHz Fourier coefficient. By doing this we were able to carry out signal offset corrections for all offset errors taking place at longer time scales than the time between the measurement in the dump gap and the first bunch, i.e. longer than about 1 μs.

Performing such bunch phase and length measurements every 13th turn yielded a sample frequency of 3.64 kHz. This was sufficiently high to observe typical synchrotron oscillations with frequencies of 20 Hz to 40 Hz and bunch length oscillations with frequencies of 40 Hz to 80 Hz. In addition this high sample frequency provides good conditions for digital filters.

3.3 Errors of Measured Signals

For an estimation of the errors we took data from measurements of the bunch phase and bunch length of a quiet bunch. By plotting the number of measurements with a certain deviation from the average over the deviation, one gets the distribution function of the error of single shot measurements. One can reduce the measurement error by low pass filtering. In figure 7 the error distribution before and after filtering of bunch phase data is shown.

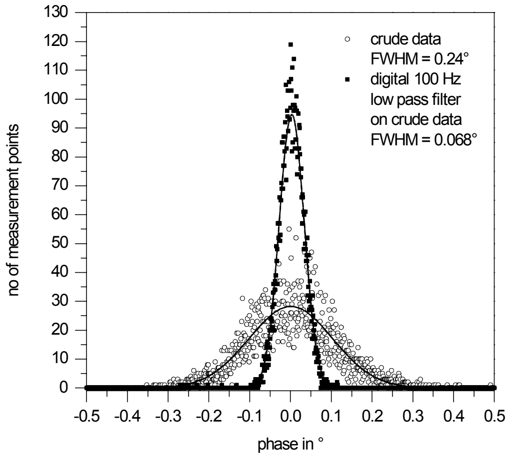

Figure 7: Error distribution of bunch phase measurement.

In figure 8 one can see the error distribution of the bunch length[1] measurement from the crude data and after filtering.

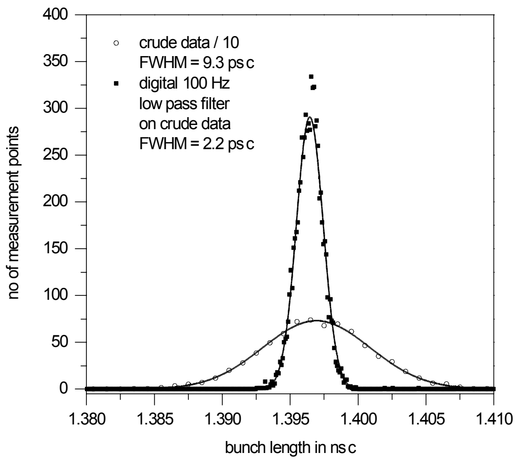

Figure 8: Error distribution of bunch length measurement.

[1]In HERA is $\beta = \frac{v}{c} \geq 0.9997$. One measures bunch signals in the time domain in seconds with signal "lengths" t_{FWHM}. These are connected with the bunch lengths in meters by $l_{FWHM} = \beta\, c\, t_{FWHM} \approx t_{FWHM}\, c$. This means $l_{FWHM} \approx \frac{t_{FWHM}}{ns}\, 0.3\, m$.

4 OBSERVED BEAM ECHOES

In figure 9 and 10 typical beam echo signals in the HERA proton storage ring at 920 GeV are shown.

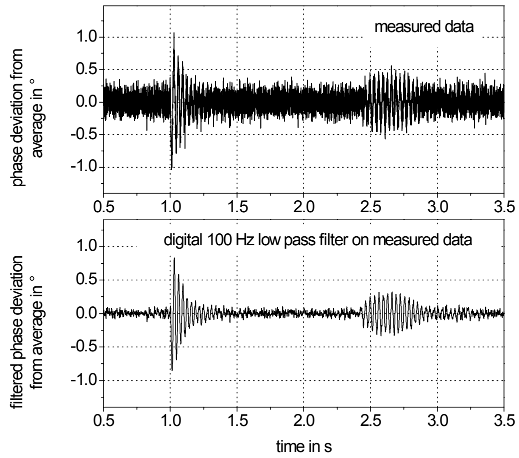

Figure 9: Bunch phase oscillation during a beam echo measurement.

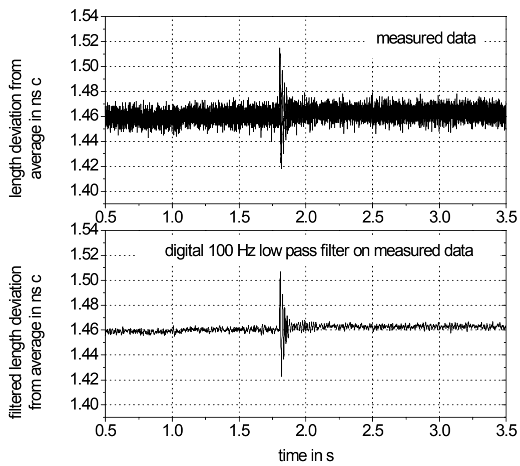

Figure 10: Bunch length oscillation during a beam echo measurement.

Both kicks were 4 ms long. The dipole kick strength was about 40 kV and the quadrupole kick about 65 kV. With a sum voltage of approximately 600 kV one obtains the kick angle for the dipole kick

$$\Delta\phi_{\text{kick}} = \arctan\frac{40\,\text{kV}}{600\,\text{kV}} = 3.8°.$$

In the measurement shown the dipole kick was applied 1 s after the trigger started the measurement and the quadrupole kick at 1.8 s so that one can observe the echo at the time $1\,\text{s} + 2 \times 0.8\,\text{s} = 2.6\,\text{s}$. Filtering the data with a 100 Hz low pass filter delivers much clearer conditions for further data analysis.

Figures 11 and 12 show a zoomed view of the beam response.

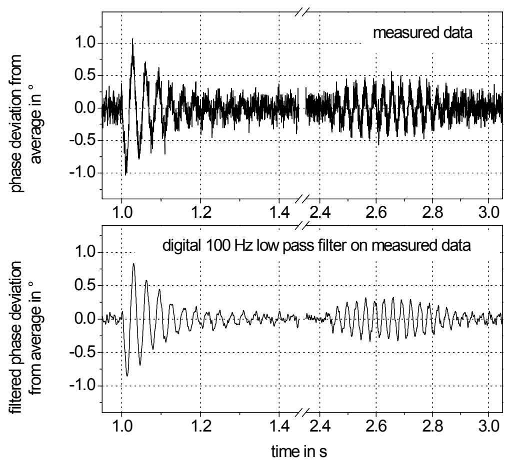

Figure 11: Zoomed view of bunch phase oscillation during a beam echo measurement.

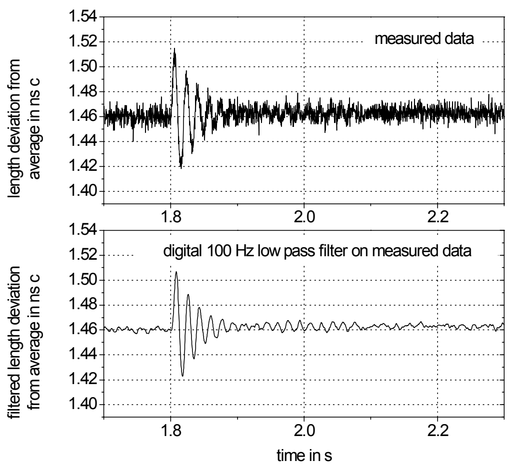

Figure 12: Zoomed view of bunch length oscillation during a beam echo measurement.

Both kicks act very cleanly. This means, that the dipole kick only excited dipole oscillations, there is no oscillation signal of the bunch length. The quadrupole kick only excites a quadrupole oscillation and no dipole oscillation.

In figure 10 you can see a small bunch lengthening at the time of the dipole kick as a result of the filamentation process.

5 FIRST ANALYSIS

The measurements presented here are the first beam echo measurements made in the HERA proton storage ring. Therefore the final goal of these studies was to prove that we have all relevant technical details under control for future beam echo studies. During previous studies many parameters which are important for an accurate data analysis were not controlled. For example we had no exact measurement of the cavity voltages etc. There are many possibilities for further improvements. It will be interesting to see the results of these improvements when the luminosity upgrade is finished and the HERA proton storage ring is in operation again.

5.1 Landau Damping

An important effect for the longitudinal stability of a proton storage ring is Landau damping. The value of the landau damping time is supplied in passing by the echo experiments. By fitting

$$\Delta\phi\,(t) = \Delta\Phi\, e^{-\,t\,/\,\tau_{\text{Landau}}} \sin\left(\omega_{\text{synchrotron}}\, t\right)$$

to the beam phase oscillation response to the dipole kicks one obtains the damping time τ_{Landau}, which we used here to quantify the Landau damping. This formula is not exact but was used to simplify the first data analysis.

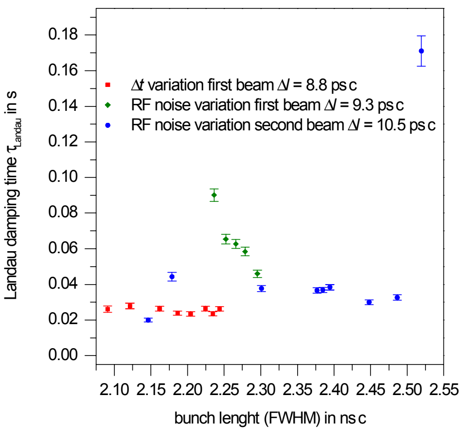

Figure 13: Landau damping time at 40 GeV. Δl is the average bunch lengthening per dipole kick for a measurement series.

Figure 13 shows Landau damping values at 40 GeV determined from different series of beam echo measurements. At this energy we deal with a very nonlinear bucket because both RF systems are switched on. The 52 MHz system builds up the bucket. At the 208 MHz system three of the four cavities are in phase and one runs with a phase shift of 180° and compensates most of the voltage of these three cavities. The remaining 208 MHz voltage leads to a strong non-linearity in the bucket. The more nonlinear a bucket is, the bigger is the Landau damping.

At 920 GeV the buckets are built up from three in-phase 208 MHz cavities and the 52 MHz cavities contain less voltage than at 40 GeV. The result is a more linear bucket and one observes less Landau damping, see figure 14.

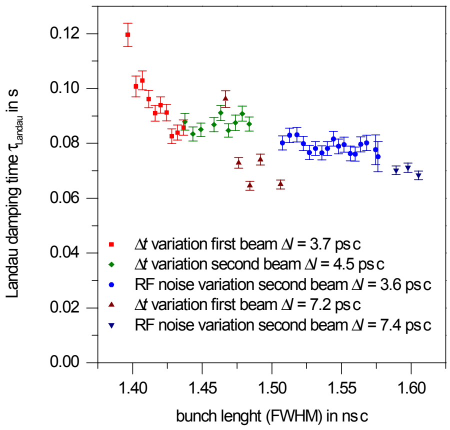

Figure 14: Landau damping time at 920 GeV. Δl is the average bunch lengthening per dipole kick for a measurement series.

One would expect a dependence of the Landau damping time on the bunch length. The longer a bunch is, the more nonlinear is the behavior. This means that the bigger the oscillation amplitude of a single proton is, the lower is its synchrotron frequency. A bigger spread of synchrotron frequencies inside a bunch leads to more Landau damping. At 920 GeV one can see a dependence of the damping time on the bunch length, see figure 14. Why this is not the case at 40 GeV is not yet clear. Perhaps the special bucket shape plays a role.

5.2 Echo Strength over Δt

The main motivation to set up beam echo measurements was to measure the dependence of the beam echo strength on the time difference between the dipole and quadrupole kick $\Delta t = T_{\text{quadrupole}} - T_{\text{dipole}}$. We hope to learn more about diffusive processes from the measured curve, such as intra-bunch scattering or processes caused by RF noise etc.

Unfortunately the shape of the echo amplitude is very sensitive to the quadrupole kick strength [3, figure 16]. Thus the maximum amplitude of the echo per maximum amplitude of the initial dipole oscillation is not a very good indicator for the echo strength. The integral over the echo amplitude seems to depend less on the quadrupole kick strength [3, figure 16]. For data analysis we used the ratio of the integrals over the absolute value of the oscillations instead. This means that for the dipole kick response we took the value

$$\Sigma_{\text{dipole}} = \int_{T_{\text{dipole}}}^{T_{\text{quadrupole}}} |\Delta\phi(t)|\, dt$$

and for the echo strength the value

$$\Sigma_{\text{echo}} = \int_{T_{\text{quadrupole}}}^{T_{\text{quadrupole}} + 2\,\Delta\, t} |\Delta\phi(t)|\, dt.$$

We first subtracted the noise

$$\frac{\Sigma_{\text{noise}}}{s} = \frac{\int_{T_0}^{T_{\text{dipole}}} |\Delta\phi(t)|\, dt}{T_{\text{dipole}} - T_0}$$

from the strength of the dipole kick

$$\Sigma_{\text{dipole,corr}} = \Sigma_{\text{dipole}} - (T_{\text{quadrupole}} - T_{\text{dipole}})\frac{\Sigma_{\text{noise}}}{s}$$

and the echo

$$\Sigma_{\text{echo,corr}} = \Sigma_{\text{echo}} - 2\,\Delta t\frac{\Sigma_{\text{noise}}}{s}$$

before calculating the ratio between direct response and echo

$$\frac{\Sigma_{\text{echo,corr}}}{\Sigma_{\text{dipole,corr}}}.$$

The fluctuation of the noise amplitude is equivalent to the uncertainty of the calculated kick strength.

Figure 15 shows the echo strength divided by the dipole kick strength versus the time deviation between the two RF kicks at 40 GeV.

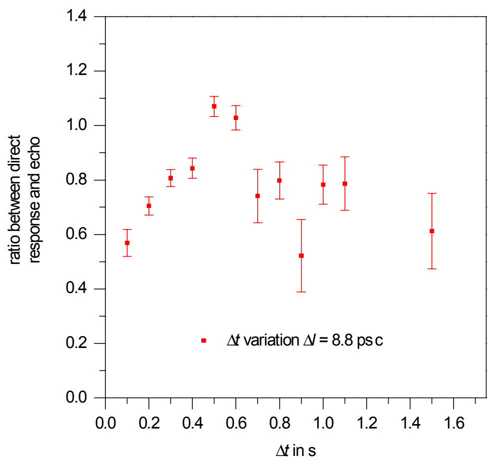

Figure 15: Echo strength as a function of the time delay between the two RF kicks at 40 GeV.

At 920 GeV we took three measurement series with different parameters and got the result shown in figure 16. As

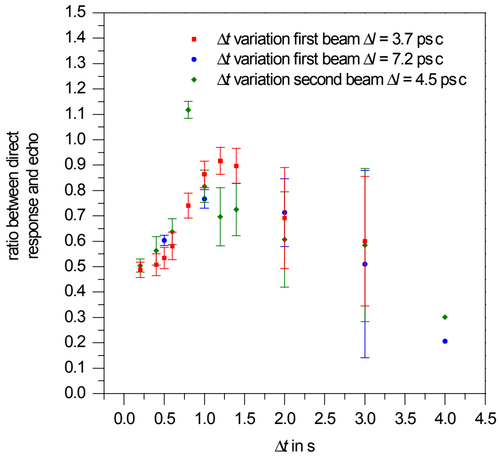

Figure 16: Echo strength over the time delay between the two RF kicks at 920 GeV.

previously mentioned, the dipole kick always causes bunch lengthening. While the filamentation process depends on the bunch length it depends also on the bunch lengthening. Therefore the averaged value of the lengthening per dipole kick Δl for each measurement series is indicated.

5.3 *Echo Strength over RF Noise*

In view of the coasting beam problems at the experiment HERA-B, the question came up whether RF noise could cause coasting beam.

In principle one can analyze the influence of RF noise on the bunched beam by observing the ratio of coasting beam current to bunched beam current over long time periods during an application of RF noise to a random modulation of the set points of the RF systems. Such measurements take a lot of time. If one could observe the effect of RF noise on the echo strength, beam echo measurements could be used as a complementary examination method which would be much faster.

We checked whether we can observe a change of the echo strength with constant time deviation between the kicks as a function of RF noise. One would expect smaller echo strength at higher RF noise levels. Higher RF noise causes more protons in a bunch to lose information about the initial dipole kick, and therefore the echo will be smaller.

Figure 17 shows the echo strength over RF noise at 40 GeV and figure 18 the situation at 920 GeV.

Both figures show a constant behavior i.e. we observed no influence. This could be due to the relatively short time delay between the kicks in combination with the relatively low noise levels. In future one should try to increase the time delay between the kicks until one can no longer measure echoes.

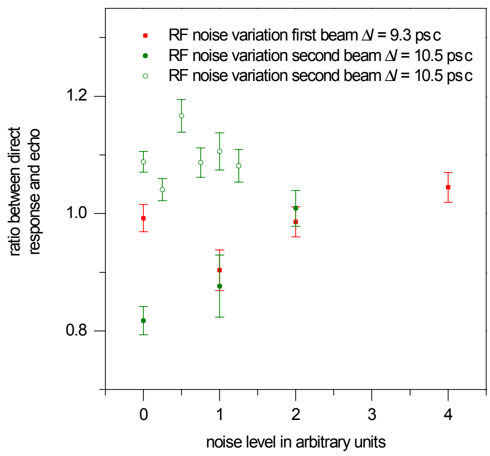

Figure 17: Echo strength over RF noise at 40 GeV.

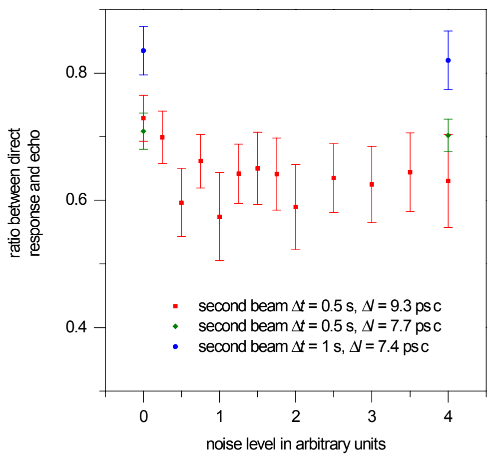

Figure 18: Echo strength over RF noise at 920 GeV.

6 CONCLUSION

We have shown that we have longitudinal bunched beam echo experiments at the HERA proton storage ring under control. The signal quality received is rather good and indicates that good measurement results could be reached by a further development of these experiments.

We measured at 40 GeV and at 920 GeV. In both cases the Landau damping times were obtained. When we changed the time delay between the RF kicks we have seen a noticeable dependence of the echo strength on this time delay. By using an automated measurement setup one could expect good enough results to compare them with theory. The dependence on RF noise resulted in a non uniform picture. Here we should increase the time deviations between the kicks and repeat the measurements.

7 ACKNOWLEDGMENTS

We would like to thank Richard Wagner and Jozef Baran from the proton RF group for their support by modifying the RF control loops, as well as Hong Gong Wu from the machine software group for adding the needed special features to the ADC server software.

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