BUNCHED BEAM ECHOES IN THE HERA PROTON RING

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Abstract

Echo experiments are a powerful tool for the study of diffusion processes in many-body systems. Beam echo measurements have been introduced to several proton accelerators for the study of incoherent beam dynamics. Usually, they have been applied to a coasting beam. In this paper we will present beam echo measurements for a bunched beam in HERA-p. An RF phase kick was used to excite bunch phase oscillations. After these oscillations had decayed due to the incoherent frequency spread, they were partly recovered as an echo by performing an RF amplitude kick.

Realistic simulations, considering HERA's double harmonic RF system, are compared to the measurements. We cannot specify all the relevant system parameters, but nevertheless the simulations agree with the measurements quite well.

1 INTRODUCTION

While coherent excitations of many-particle systems often decay in amplitude with time due to a spread of particle oscillation frequencies, sometimes echoes of decayed excitations can arise when the oscillations are manipulated appropriately.

Electromagnetic wave echoes in a plasma and echoes of magnetization of a spin ensemble in solids have long been known in plasma and solid state physics. To accelerators echoes have been introduced in [1]. These echoes can occur in density fluctuations of a coasting beam as well as in longitudinal or transverse bunched beam coherent oscillation amplitudes.

The beam echoes are expected to provide powerful diagnostic techniques and were mostly investigated to try to estimate so called 'diffusion coefficients' , which can be related to RF noise, intrabeam scattering and other 'stochastic' processes that play a role in a proton storage ring [2], [3]. However, this approach has not been satisfactorily exploited up to now.

From the experimental point of view, it was first possible to observe longitudinal coasting beam echoes in 1995 at Fermilab and then in the CERN SPS. In September 2000 longitudinal bunched beam echoes were produced in the HERA proton ring and we will present some computational analysis of these measurements. This analysis is part of research performed to get a better understanding of the longitudinal proton dynamics in HERA.

2 BUNCHED BEAM ECHOES

The longitudinal single particle motion in (ϕ, δ) phase space, where ϕ is the particle deviation from a reference phase and δ is the particle's relative deviation from the reference energy, can be approximated by a smooth model with

$$\dot{\phi} = \frac{2\pi h}{\beta^2 T_0}\eta\delta, \qquad \dot{\delta} = \frac{e}{T_0}\frac{V'(\phi)}{E_0}. \tag{1}$$

Here $V(\phi)$ is the potential produced by RF cavities, h is the harmonic number, E - the energy of the reference particle, η - the slippage factor and β - the relativistic factor.

Provided the initial distribution function in (ϕ, δ) phase space $f(\phi_0, \delta_0)$ is given, we can find the dipole moment

$$<\phi>=\int_{-\infty}^{\infty}\phi(\phi_0, \delta_0, t) f(\phi_0, \delta_0) d\phi_0 d\delta_0 \tag{2}$$

where $\phi(\phi_0, \delta_0, t)$ is the solution of our equations.

To the first approximation our system is a linear oscillator, and the solutions are just phase-space rotations with synchrotron frequency ω_s. When $V(\phi) = A(1 - \cos(\phi))$ the solution can be found analytically with the help of elliptic functions, but for more general cases Hamiltonian perturbation theory should be applied. In second-order approximation the solutions are amplitude dependent rotations with frequencies $\omega = \omega_s + \omega_1(\hat{\phi}^2 + \hat{\delta}^2)$, where $\hat{\phi}$ and $\hat{\delta}$ are some normalized coordinates.

Since particles with different amplitudes have different frequencies, any perturbation of the distribution that is not symmetric around the origin will smear out after some time. The rate of this 'filamentation' depends on the properties of the distribution and on the mixing properties of the system that are in first approximation described by ω_1. For some distributions $<\phi>$ can be found analytically and thus explicit dependencies of decoherence on various parameters can be studied [1], [4].

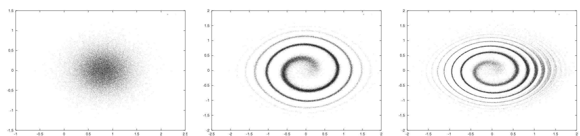

Figure 1: Phase-space filamentation (center) of a kicked Gaussian beam (left) and the occurance of an echo (right).

The bunched beam echo is usually produced as follows: first a dipole kick is made that shifts the distribution along the ϕ-axis , that is $f(\phi, \delta, t_0^+) = f(\phi - \Delta\phi, \delta, t_0^-)$, and causes a non-symmetric perturbation to evolve. Then, after this perturbation filamented into spirals around the origin and caused the dipole oscillation to cease, a quadrupole kick is applied. After this kick the new distribution function is given by $f(\phi, \delta, t_+) = f(\phi, \delta + q\sin(\Omega\phi), t_-)$. This causes the spiraled perturbation to deform and rearrange. After some time this results in recovering of the initial phase space perturbation. In the sequel we show how this phenomenon is reproduced with straightforward simulations using the turn-by-turn map

$$\phi_{n+1} = \phi_n + \frac{2\pi h}{\beta^2}\eta\delta_n, \quad \delta_{n+1} = \delta_n + e\frac{V'(\phi_{n+1})}{E_0}. \quad (3)$$

For the HERA proton ring we consider the double-harmonic potential $V(\phi) = U_1(1 - \cos(\phi)) + U_2(1 - \cos(\frac{\phi}{4}))$.

Relevant HERA parameters are the following: harmonic number $h = 4400$, slippage factor $\eta = 0.012827 - \frac{1}{\gamma^2}$, the proton ring has four 208 MHz cavities, one having a voltage of -30kV and three having approximately 200kV each during a luminosity run. The two 52MHz cavities have then around 90kV each. The bunch length just after the ramp is about 1.4 ns, but measurements were performed with bunch length up to about 2 ns.

We neglect the effect of wake fields since the impedances at fundamental cavity frequencies are suppressed by feedback and the total effect of wake fields on the time scales studied should not influence our dynamics much.

3 MEASUREMENT SETUP

3.1 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 cavity. 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 system of one 208 MHz cavity.

To generate two rectangular signals with programmable amplitude, width, and time separation between them, we used a four channel pulse generator, controlled via a GBIB connection. This generator also provided a trigger signal to a new fast longitudinal diagnostic system [5].

The 52 MHz RF system provides a feed forward compensation input for an additional RF signal to compensate beam loading. We used this input to add an 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 LO signal we took the 52 MHz RF reference. By supplying the I/Q demodulator at the I input with the first rectangular signal from the pulse generator and the Q input with the second one we produced two RF bursts with a phase relation of 90^o .

Figure 2 shows 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.

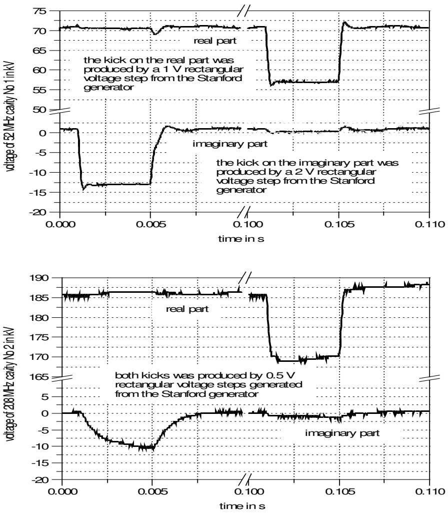

Figure 2: Kicks at 52 and 208 MHz

At the 208 MHz system we changed the set points of the amplitude and phase regulation loop with the pulse generator to produce the required kicks as shown in figure 2. A more detailed description of the necessary changes to the RF system can be found in [6].

3.2 Bunch Measurements

The bunch signal received from a resistive gap monitor excites an oscillation in a 52 MHz band pass filter. The maximum amplitude of this signal is a measure of the 52 MHz Fourier component of the bunch spectrum. The phase of the oscillation is a measure of the bunch phase $< \phi >$.Both pieces of information are obtained with an I/Q demodulator. By using a 208 MHz band pass filter and a RF diode a second Fourier coefficient is determined. Assuming a specific bunch shape, we calculate the bunch length from these two Fourier coefficients.

4 OBSERVED AND SIMULATED ECHOES

We restrict the comparison to 920 GeV, since at low energies the RF voltages can currently not be measured with sufficient accuracy. For simulations we took three different initial distribution functions

$$f_1(\phi, \delta) = \frac{1}{\sqrt{2\pi}\sigma_\phi\sigma_\delta} e^{-0.5((\frac{\phi}{\sigma_\delta})^2 + (\frac{p}{\sigma_p})^2)}, \quad (4)$$

$$f_2(\phi, \delta) = K - \sqrt{H}, \quad f_3(\phi, \delta) = \sqrt{K - H}, \quad (5)$$

where $H = \frac{\delta^2}{2} + A_1(1 - \cos(\phi)) + A_2(1 - \cos(\frac{\phi}{4}))$ is the Hamiltonian of the smoothed model of equation (1).

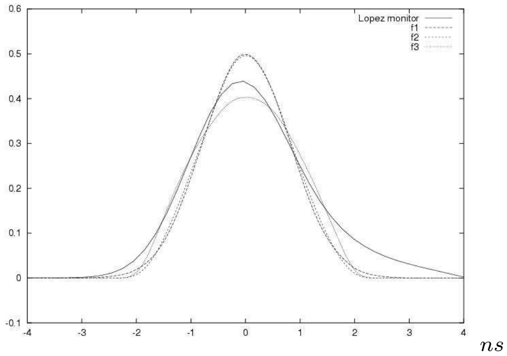

Figure 3: Three test distributions and the measured bunch profile

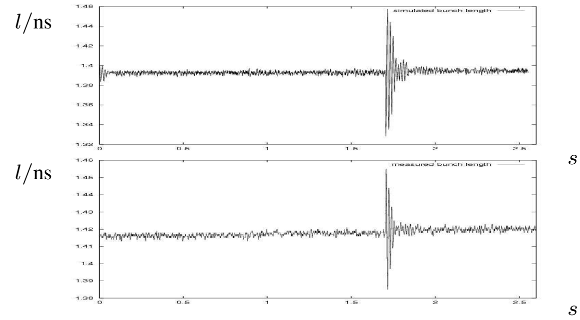

Figure 5: Simulated (top) and measured (bottom) bunch length l during echo production

The parameters of these distributions were chosen to fit the bunch length which is defined as the interval where 71.6% of particles reside.

The simulated and measured dipole responces for a Gaussian distribution f_1 are shown in figure 4. In general, the less frequency spread we have in the distribution, the flatter the echo envelope and the longer it takes for the perturbation to decohere. If we take a parabolic distribution, the decoherence time will decrease, so we can fit the dipole moment measurements quite closely with a linear combination of f_1, f_2 and f_3.

For a Gaussian distribution a dipole kick produces a rather strong quadrupole moment which was not observed experimentally, for the distribution f_3 the decoherence is not fast enough. The distribution f_2 most closely fits both bunch center and bunch length measurements. The simulated and measured bunch length are shown in figure 5.

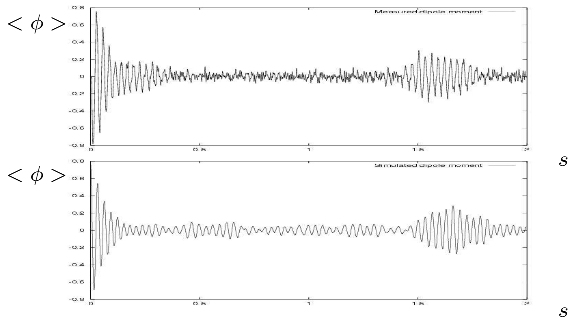

Figure 4: Measured (top) and simulated (bottom) echo signals $< \phi >$

Various processes like interaction with wake fields, coupling with the betatron motion, RF noise , intrabeam scattering and many others can influence the correlation between particles and hence generally reduce the echo amplitude. The simulated dependency of echo strength on kick delay is shown in figure 6. The measured echo decays with the delay between the two kicks somewhat slower than the simulated one. This we cannot explain yet, but the effect can by no means hint at any noise processes. It rather indicates that the real map should noticeably deviate from equation (3) or the beam distribution should be simulated differently.

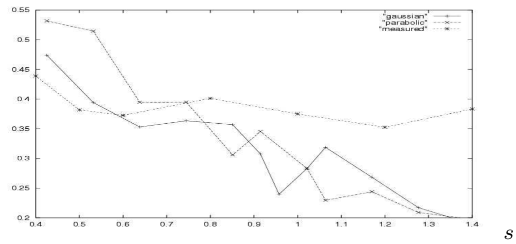

Figure 6: Echo aplitude vs. kick delay

Acknowledgements

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