BUNCHED BEAM ECHOS IN THE AGS

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Abstract

Beam echos have been measured at FNAL [3] and CERN [5] in coasting beams. A coherent oscillation introduced by a short RF burst decoheres quickly, but a coherent echo of this oscillation can be observed if the decohered oscillation is "bounced off" a second RF burst.

In this report we describe first longitudinal echo measurements of bunched beam in the AGS accelerator. We applied a method proposed by Stupakov [1] for transverse beam echos, where the initial oscillation is produced by a dipole kick and is bounced off a quadrupole kick. In the longitudinal case the dipole and quadrupole kicks are produced by a cavities operating at a 90° and 0° phase shift, respectively. [1]

1 INTRODUCTION

The echo effect is well known in plasma physics and was first introduced to accelerator physics by Stupakov [1]. In his 1992 paper he proposed the use of a dipole kicker to produce a coherent transverse bunch oscillation which decoheres rapidly because of Landau damping. After a time t much larger than the decoherence time, a quadrupole kicker is fired for one turn. The kick does not produce any immediate coherent motion, but "rearranges" the particle distribution in phase space so that after another time interval t the "echo" of the initial coherent oscillation appears.

This method can be applied directly to the longitudinal motion. The dipole kicker is replaced by a cavity phased to accelerate the beam at the top of the wave, the quadrupole by a cavity phased to focus the beam at the node of the wave. Such cavities can be turned on and off more easily than a magnet and, since the longitudinal tune is small ($\nu_s \approx 10^{-4}$), the cavity may be turned on for several turns.

The condition under which echoes can be observed is simple: the particles perform an oscillation where the amplitude is constant and the phase advance depends only on the initial coordinates of the particle. In this case the future motion of a particle is determined simply by its amplitude. The echo can then be generated by changing the amplitude of particles which will have the wrong phase when the oscillations recohere.

This condition is perfectly fulfilled for the longitudinal motion of coasting beams. The phase advance depends only on the energy of the particle. The condition is also fulfilled for bunched beams, where the phase advance is approximately:

$$\Delta\phi = \Delta\phi_0 \cdot \left(1 - \frac{\epsilon^2}{\epsilon_0^2}\right)$$

$\Delta\phi_0$ is the linear phase advance, A is the longitudinal emittance of the particle and ϵ_0 is the emittance on the separatrix.
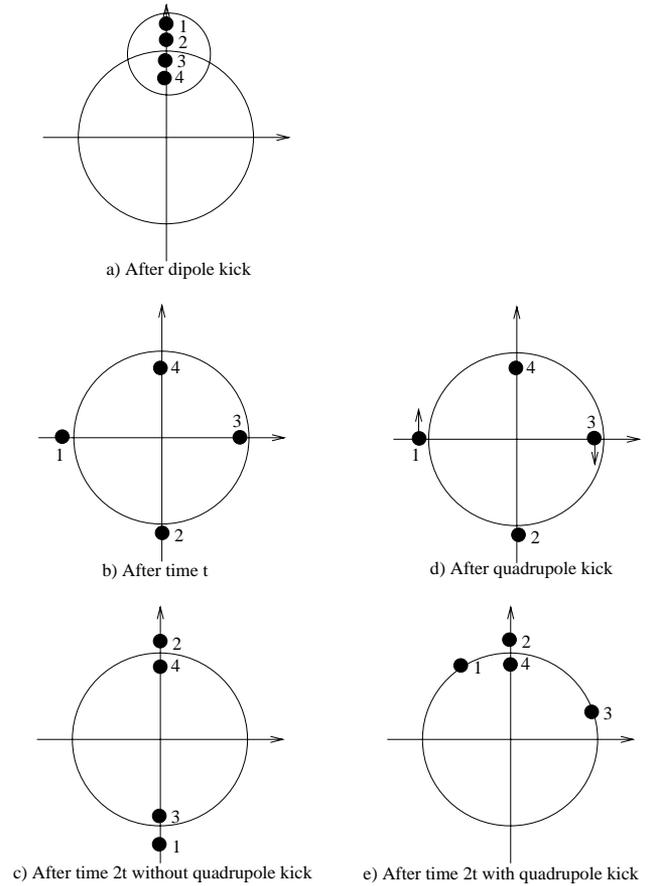

a) After dipole kick

b) After time t

d) After quadrupole kick

c) After time 2t without quadrupole kick

e) After time 2t with quadrupole kick

Figure 1: Explanation of the echo mechanism in phase space

An "anschauliche" explanation of the echo effect is given in Fig. 1. The horizontal axis is the longitudinal displacement s and the vertical axis is the energy deviation $E - E_0$. Fig 1a. shows the bunch (represented by the small circle) after the initial dipole kick. All particles have received additional energy, so the beam is shifted up in phase space.

We observe four particles of this bunch which are for simplicity selected so that after some time t the phase advanced is $(n_1 + \frac{1}{4}) \cdot 2\pi$, $(n_2 + \frac{1}{2}) \cdot 2\pi$, $(n_3 + \frac{3}{4}) \cdot 2\pi$ and $(n_4 + 1) \cdot 2\pi$, respectively with $n_1 < n_2 < n_3 < n_4$. The center of mass for these particles is approximately zero, the coherent motion has disappeared (Fig.1b).

If no quadrupole kick is applied, these particles end up after another time t in the positions shown in Fig. 1c and

the average motion is still zero. However, if we apply a quadrupole kick, the amplitudes of particles 1 and 3 are changed (Fig. 1d) and they will not end up in a position to balance particles 2 and 4 (Fig. 1e). Therefore an echo is observed.

This simple picture of the echo process explains why an echo can be observed at time t after the quadrupole kick, independent of the time t and the strength of the kick. It does not explain the shape or phase of the echo. These quantities depend on the initial distribution of the particles and the strength of the quadrupole kick.

The echo is produced by tiny changes of the amplitudes by the quadrupole which causes large changes in the phase advance. Any effect that changes the amplitude of the particles, like RF noise or intra-beam scattering, will therefore destroy the echo. Measuring the amplitude of echos with varying delay times is a tool to measure the diffusion time of such effects. The echo effect in the presence of diffusion is studied by Stupakov and Chao in [2].

Of special concern to the operation of RHIC is intra-beam scattering which may limit to the integrated luminosity. In preparation for echo measurements in RHIC we performed an experiment in the AGS accelerator. The goal of our experiment was a proof of principle that echos can be observed in bunched beams in order to measure the growth of the beam from intra beam scattering.

2 AGS MEASUREMENTS

The AGS is a synchrotron with a cycle time of 3 seconds. The radius of 807.12 m. It is used as a source of particles from protons (30 GeV) to gold (12 Gev) for fixed target physics. The echo experiment was performed after a run producing iron ions at 1.8 Gev. Time did not permit changes of any machine parameter. Because of the synchrotron cycle only a time interval of 100 msec ($\approx 10^5$ revolutions) could be used.

The RF system consists of 10 cavities. Because of the relatively low energy of the beam one of the ten cavities was dedicated to produce the longitudinal dipole and quadrupole kick.

In order to observe longitudinal oscillations of the beam the feedback system for phase correction had to be disabled. It turned out that without the feedback the bunches made oscillations comparable to the expected effect. This problem was also observed at CERN. [6]

The solution to this problem was to kick the four bunches in alternating directions. This was accomplished by operating the kicker cavity with half the usual frequency ($h = 6$ instead of $h = 12$). The average phase signal was not affected by the echo experiment. The feedback system could be left turned on. The coherent oscillations of the echo process were then measured with a spectrum analyzer at the frequency corresponding to $h = 6$.

The results of the measurement are shown in Figure 2 and 3. The beam is kicked in both measurements by $\approx 20\%$ of its initial width. Figure 2 shows the beam signal when only the dipole kick is given. The resulting oscillation decoheres within 14 msec. No echo is observed. Figure 3 shows the same dipole kick followed by a quadrupole kick at 15.7 msec. This produces a number of echos with decreasing amplitude, as predicted by the theory. Only after the end of the measurement we realized that something was wrong with this picture: the first echo appears after twice the predicted time.
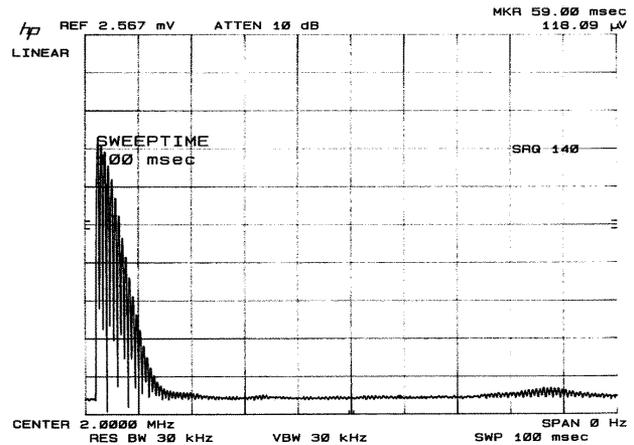

Figure 2: Coherent Beam signal (linear scale) with a single dipole kick. The horizontal axis is the time, the width of the graph is 100 msec.
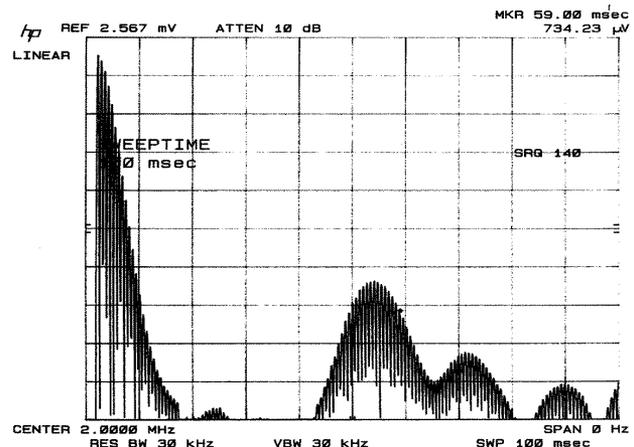

Figure 3: Coherent Beam signal with a dipole kick followed by a quadrupole kick

The explanation, verified with a tracking program, is that the echo produced in our setup had not opposite phase for alternating bunches and was eliminated by the feedback system. What we measured was the "echo of the echo". Unfortunately, we had no chance to repeat the measurement with the correct setup. More studies will be performed when RHIC is operational.

3 COMPUTER SIMULATION

A simple tracking program was written to understand the interaction between echoes and the feedback system. The program generates two bunches with a Gaussian distribution of 10000 particles each and follows the motion over 80000 revolutions. The program records the sum and difference of the average longitudinal position of the two bunches.

Figure 4 shows the difference signal for a dipole kick with $h_d = 6$ and a quadrupole kick with $h_q = 12$. The sum signal remains zero. This is the correct setup for echo measurements.

Figure 5 and 6 show the difference and sum signal, respectively, where both the dipole and quadrupole kick has $h_d = h_q = 6$. The echo appears in the sum signal. This is what we would have measured with the feedback system turned off.

Finally, Figure 7 shows the the same situation with the feedback system turned on. The sum signal is forced to be zero, and the echo appears after twice the time in the difference signal.

4 CONCLUSION

Stupakov's method of producing beam echos has been successfully applied to the longitudinal motion. The problem of phase stability has been solved by keeping the feedback system turned on. The dipole kick must be produced with an alternating direction, so that the feedback system does not eliminate the oscillation. The quadrupole kick must be the same for all bunches in order to produce an echo with opposite phase for alternating bunches.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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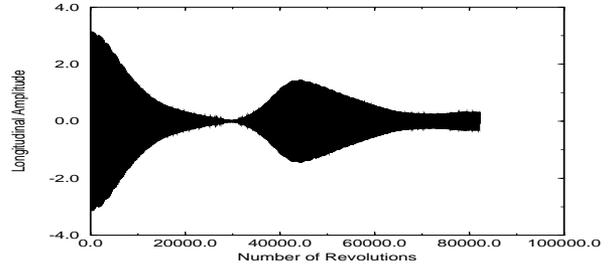
[6] O. Brünning, private communication

Figure 4: Difference signal with $h_d = 6$ and $h_q = 12$.
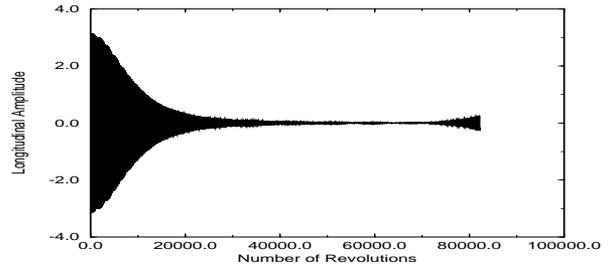

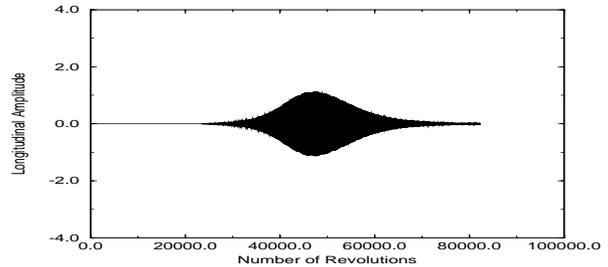Figure 5: Difference signal with $h_d = h_q = 6$.

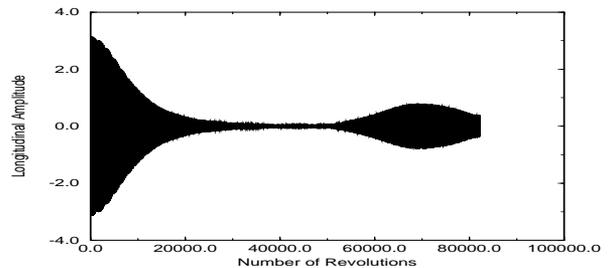Figure 6: Sum signal with $h_d = h_q = 6$.

Figure 7: Difference signal with $h_d = h_q = 6$ and phase feedback enabled.