BEAM ECHOES IN THE CERN SPS

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Abstract

Longitudinal echo signals have been produced in the CERN SPS by exciting a proton beam at 120 GeV/c with two short RF pulses separated by a suitable time-delay. The aim of the experiments was to confirm the analytical predictions for beam echoes in the SPS and to probe the applicability of beam echoes for a measurement of the energy distribution and diffusion coefficients in the accelerator. We summarise here the results obtained with bunched and un-bunched beams. For an un-bunched beam, the excitation frequencies are at different harmonics of the revolution frequency and result in an echo response at the difference frequency of the two RF kicks. For the case of a bunched beam, the RF kicks are adjusted to excite the quadrupole mode of the bunch motion and the beam echo response can also be observed as a quadrupole mode.

1 INTRODUCTION

Echo phenomena have been well known in plasma physics for many years [1]. However, the effect has only been recently introduced to accelerator physics and first measurements of the echo signal in a storage ring suggest the possibility of using echo techniques in the beam diagnosis [2][3]. This paper summarises the echo measurements in the CERN SPS with bunched and un-bunched beams.

The echo signal is an interference pattern of two consecutive short RF-pulses. In the case of an un-bunched beam, the echo signals in the CERN-SPS were generated by exciting a coasting proton beam at 120 GeV/c with two short RF pulses using the 200 MHz travelling wave RF system. Without diffusion, one can find an exact solution for the echo response in a coasting beam and one can show that the beam echo appears at a time

$$t^* = \frac{h_1}{h_2 - h_1} \cdot \triangle t \tag{1}$$

after the second RF-kick, where $\triangle t$ is the time separation of the two RF-kicks. For a non-vanishing diffusion term the echo response in the beam current is given by [4][5]

$$\begin{aligned} I_{echo}(t) \approx\ & 2e\omega_0 \cdot J_1(\epsilon_1 \tau) \cdot J_1(x + \epsilon_2 \tau) \\ \times\ & \tau \cdot \int \rho(p) \cdot e^{-ip\tau}\ dp \\ \times\ & e^{-Dk_0^2\left[h_1^2(\triangle t)^3 + (h_2-h_1)^2 \cdot t^3\right]/3}, \end{aligned} \tag{2}$$

where D is the diffusion coefficient, $\rho(p)$ the initial energy distribution with $p = \triangle E/E_0$, τ the time measured relative to the centre of the echo response,

$$\tau = k_0(h_2 - h_1) \cdot (t - t^*) \tag{3}$$

and t the time measured from the second RF kick. $J_n(x)$ are Bessel functions of the first kind with

$$x = h_1 \epsilon_2 k_0 \triangle t \tag{4}$$

and

$$k_0 = \frac{\omega_0 \eta}{\beta^2}; \qquad \eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}. \tag{5}$$

ϵ_1 and ϵ_2 are perturbation parameters

$$\epsilon_i = \frac{\omega_0 T_i}{2\pi} \cdot \frac{eV_i}{E_0}; \qquad i = 1, 2 \tag{6}$$

where $\omega_0 = 2\pi f_0$ is the revolution frequency, T_1 and T_2 the kick lengths and V_1 and V_2 the kick amplitudes of the first and second RF kick respectively. ϵ_1 and ϵ_2 are the relative energy gains during the first and second RF-kick respectively. In the following we will assume that the relative energy gain during the two RF-kicks are small compared to the initial energy spread in the distribution.

The first line in Equation (2) implies that the leading term of the echo response varies with the time separation of the two RF-kicks like a Bessel function of the first kind $J_1(x)$. The integral in Equation (2) indicates a strong influence of the energy distribution on the shape of the echo signal. In the following we will call it the form factor $F(\tau)$ of the echo response. The strong cubic dependence of the damping term on time suggests the possibility of measuring even very small diffusion coefficients within a reasonably short time interval.

In the case of a bunched beam, the echo signals in the CERN SPS were generated by applying two short amplitude reductions to the nominal RF voltage of the 200 MHz travelling wave RF system which provides the RF buckets for the proton beam at 120 GeV/c.

2 EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup for the echo measurement and Table 1 lists the relevant parameters for the CERN SPS.

f_0 [kHz]	$\lvert\eta\rvert$	E_0 [GeV]	f_{RF} [MHz]
43.23	$1.8 \cdot 10^{-3}$	120	200

Table 1: *Machine parameters of the SPS.*

3 EXPERIMENTAL DATA FOR AN UNBUNCHED BEAM

We presented first results of un-bunched beam echo measurements already in [6]. Here, we will only briefly illustrate the effect and demonstrate how the echo measurement

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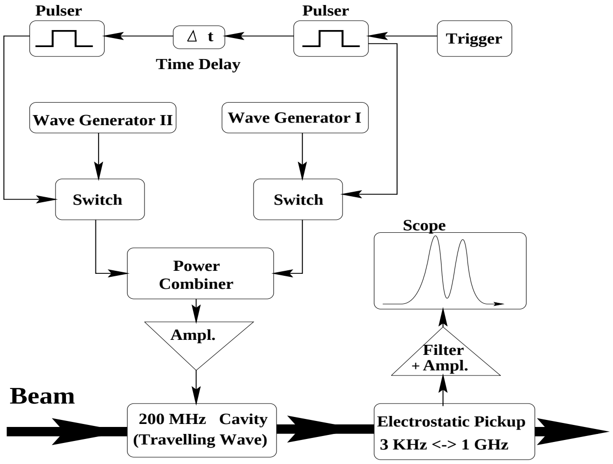

Figure 1: *Schematic setup for the echo measurements.*

can be used for measuring the diffusion coefficient. Fig. 2 shows a typical echo measurement for a kick amplitude of 500 kV. Each kick lasted for 92 $\mu\ s$ (4 turns) and the two kick have a time separation of 45 ms. Fig. 3 shows the super-imposition of 25 such measurements, each having a different time separation between the first and the second RF-kick. The time separation varies from 45 ms to 230 ms. Note that for a time separation of 230 ms the echo response occurs only 2 minutes after the second RF-kick. The envelope of the echo signals in Fig. 3 agrees qualitatively with the expected Bessel function dependence indicated in the first line of Equation (2). However, the later the echo signal appears after the second RF-kick, the larger the divergence of the measured signal from the pure Bessel function envelope in the first line of Equation (2) indicating a non-vanishing diffusion coefficient in (2). For $D \approx 10^{-13} \cdot s^{-1}$ the measured data agrees very well with the expected behaviour in (2) and corresponds to an emittance growth of

$$\triangle\sigma_{\triangle p/p_0} = 10^{-3} \tag{7}$$

in 115 days.

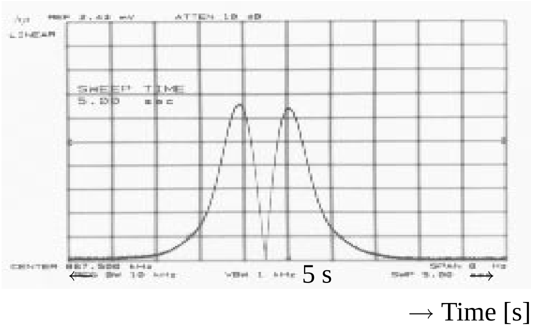

Figure 2: *The measured echo signal on a linear scale. The measured echo response corresponds to an approximately Gaussian energy distribution. The horizontal scale is 0.5 s per division.*

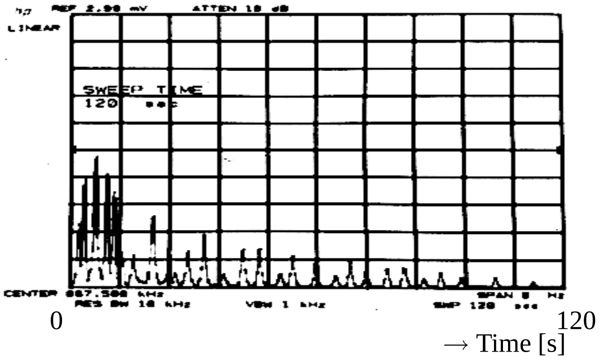

Figure 3: *The picture shows the superposition of 22 beam echos for different separation times $\triangle t$ as a function of time after the second RF kick. The time separation of the two RF kicks varies between 5 ms and 220 ms, resulting in an echo response up to two minutes after the second RF-kick.*

In [6] it was shows that the echo signal can also be used for measuring the energy distribution function and the energy spread in the beam.

4 MEASURING DIFFUSION COEFFICIENTS

The results of the previous Section indicated the possibility of measuring even very small diffusion coefficients with echo signals. This aspect was analysed in more detail by deliberately applying a noise signal to the 800MHz cavity in the SPS. The noise signal was calibrated by measuring the growth of the energy spread in the beam for different noise amplitudes from the longitudinal Schottky signal [7]. Over a time interval of 100 s, the Schottky signal was sensitive to noise signals which correspond to Once the noise signal was calibrated the noise amplitude was reduced to values where we could no longer observe a growth of the energy spread in the longitudinal Schottky signal. The beam echo could be successfully used to measure noise amplitudes which were at least two orders of magnitude smaller. Fig. 4 shows the measured diffusion coefficients versus the applied noise amplitude in dB. The points with noise amplitudes larger than -45 dB are calculated from measurements using a Schottky signal [7]. All other points are calculated from echo measurements. All data points agree with the analytical estimates and lie on a straight line with slope 1/10 in the double logarithmic plot.

5 BUNCHED BEAM ECHOES

Recent experiments in the CERN SPS extended the echo measurements to the case of a bunched beam. Fig. 5 and Fig. 6 show typical measurements, where the beam was excited with two consecutive quadrupole kicks. Each kick lasted approximately 200 $\mu\ s$. Both kicks in Fig. 5 had an amplitude of $-500\ kV$ compared to a nominal RF-voltage of $5.1\ MV$ and were separated by $\triangle t = 90\ ms$. The first kick in in Fig. 6 had also an amplitude of $-500\ kV$ but the second kick was approximately four times smaller than

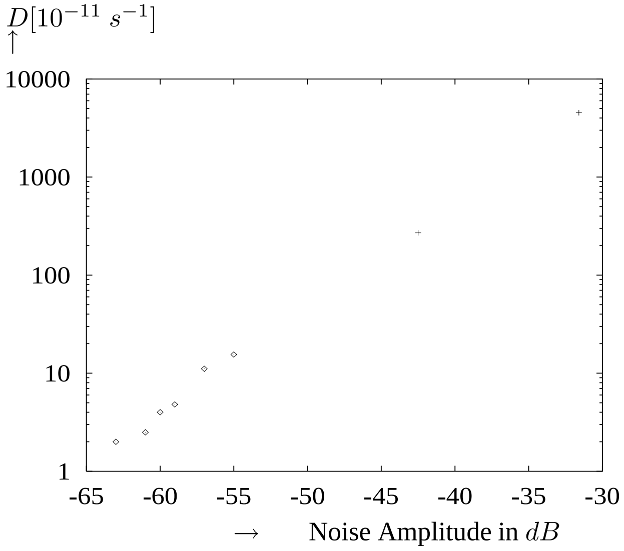

Figure 4: *Infered diffusion coefficients. The vertical axis shows the diffusion coefficients on a logarithmic scale in units of* $10^{-11}\ s^{-1}$ *and the horizontal axis the noise amplitude in* dB*. Assuming a diffusion process with white noise, one expects a straight line with slope 0.1 in this representation. The points with a noise amplitude larger than* $-45\ dB$ *are calculated from measurements using the Schottky signal. All other points are calculated from echo measurements.*

the first kick. Nevertheless the echo response in this case is more pronounced than in Fig. 5. The two kicks in Fig. 6 were separated by $\triangle t = 200\ ms$. A detailed study of the bunched beam echo is still in progress and we summarise here only the main features observed in the measurements:

- The echo signal could only be observed if the bunch filled almost the whole RF-bucket.
- The measured echo response was larger if the second RF-kick was smaller than the first kick.

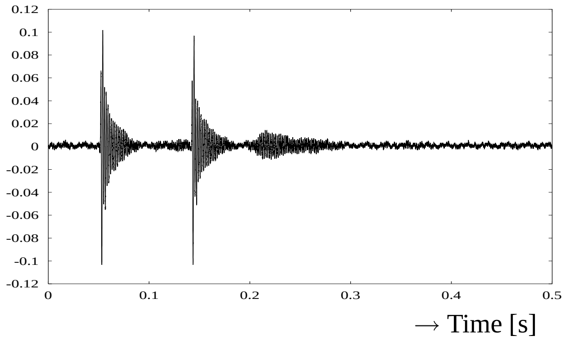

Figure 5: *The measured echo signal in a bunched beam on a linear scale for a time separation of* $\triangle t = 90\ ms$ *between the two RF-kicks. The horizontal scale is 0.5 s.*

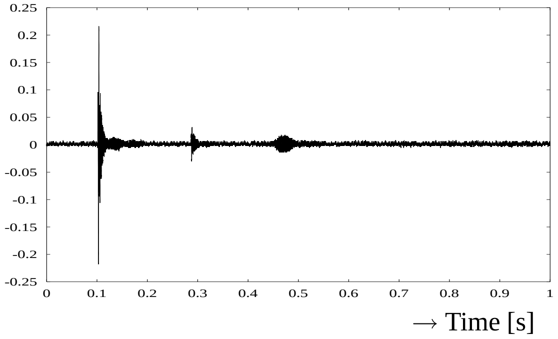

Figure 6: *The measured echo signal in a bunched beam on a linear scale for a time separation of* $\triangle t = 200\ ms$ *between the two RF-kicks. The second RF-kick is approximately four times smaller than the first RF-kick. The horizontal scale is 0.5 s.*

6 SUMMARY

The un-bunched beam echo measurements in the CERN SPS agree well with the analytical expectations and show that echo signals can be used for measuring beam distributions and diffusion coefficients. Measurements of bunched beam echoes are just starting and a detailed study of this effect is still in progress.

7 REFERENCES

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