Beam Echo Measurements

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What is a beam echo?

A second-order response due to a pair of impulse kicks applied successively in any plane.

(actually a form of three-wave coupling)

What is an echo good for?

The most important use of an echo (so far) is as a sensitive measurement of diffusion rates.

Brief History of Echoes

- Developed in the forties in magnetic materials as spin echoes
- Developed mathematically in plasmas in the sixties
- Introduced into high-energy accelerators in 1992 by Stupakov
- Found independently experimentally by Spentzouris in 1995

What types of echoes have been observed?

Longitudinal coasting beam

- Fermilab Antiproton Accumulator
- CERN SPS

Longitudinal Bunched Beam

- Fermilab Tevatron
- CERN SPS
- DESY-HERA

Transverse Bunched Beam

- CERN SPS

Longitudinal Coasting Beam Echo

$$I_{echo} = -\left(\frac{e\omega_0}{2\pi}\right)^3 \sum_{n'} \frac{1}{(n-m)n'k_0^2} \int \frac{ds'}{2\pi i} \frac{V_{-n'+m-m} V_{n'}}{D_{-n'+m-m}(s-s') D_{n'}(s') D_{n-m}(s)}$$

$$\cdot \int d\epsilon\, \tilde{F}_{n-m}(\epsilon, s) \frac{\partial}{\partial \epsilon}\left\{\frac{\partial f_0}{\partial \epsilon} \tilde{F}_n(\epsilon, s')\right\}$$

$$\tilde{F}_{n-m}(\epsilon, s) = \int_0^\infty du \exp\left\{i \frac{s + i(n-m)(\omega_0 + k_0\epsilon) u}{(n-m)k_0} + \frac{i\nu\epsilon_0^2 u^3}{3(n-m)k_0}\right\}$$

$$D_{n-m}(s) = 1 - \left(\frac{e\omega_0}{2\pi}\right)^2 Z_{n-m} \int \frac{d\epsilon \frac{\partial f_0}{\partial \epsilon}}{s + i(n-m)(\omega_0 + k_0\epsilon)}$$

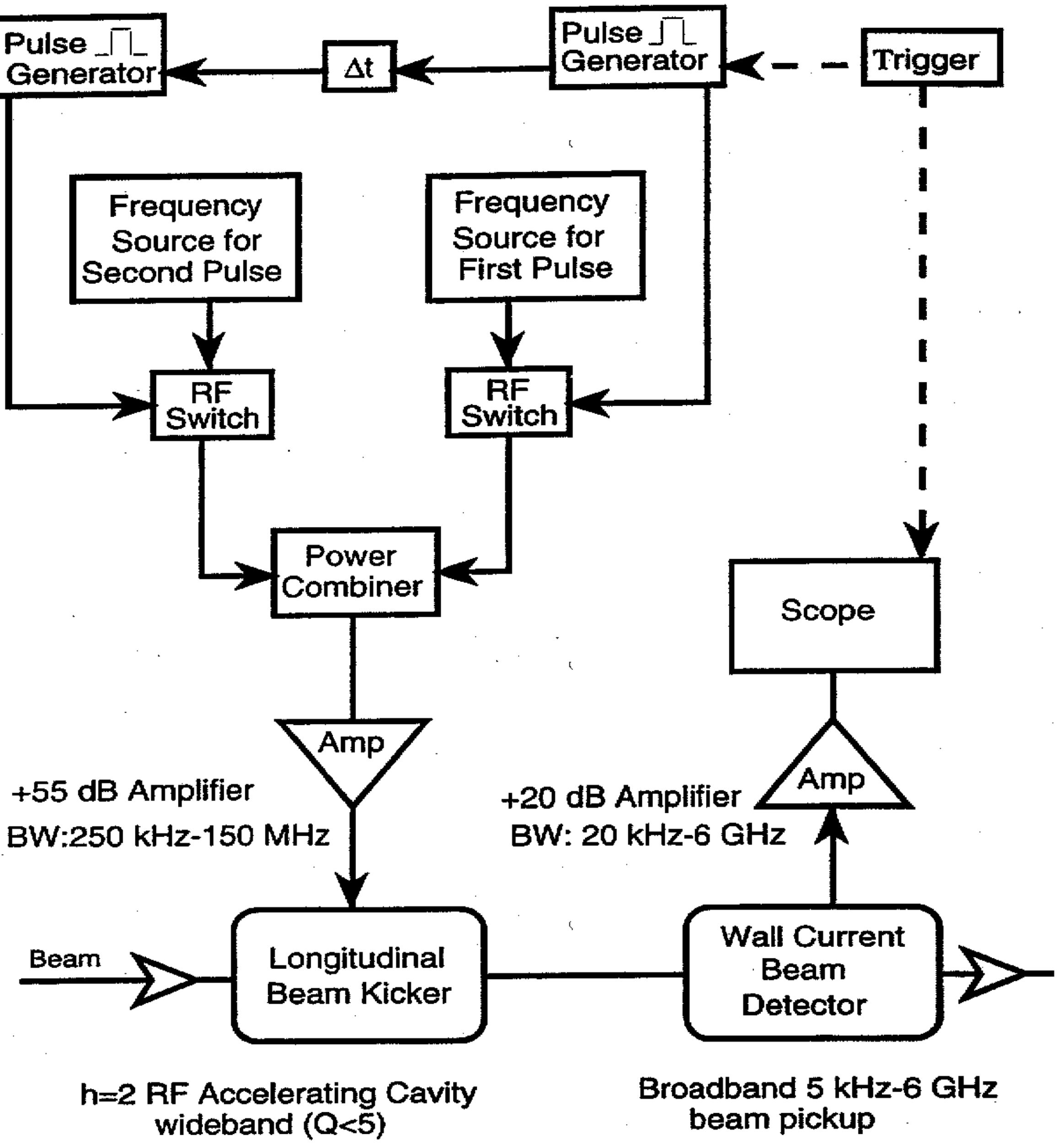
$$\underset{\text{envelope}}{I_{echo}} \sim J_1(2m\delta k_0\epsilon_0 \Delta t) \exp\left\{-\nu k_0^2 \epsilon_0^2 \frac{n^2(n-m)^2}{3m^2}\right\}$$

$(D_n \to 1$ No Wakes$)$

Longitudinal Bunched Beam Echo

$$\underset{\text{envelope}}{\langle \tau \rangle_{echo}} \sim \frac{\partial \omega_{s0}}{\partial J} J_0 t_1 \left(1 + \frac{8}{3} D_0 \left[\frac{\partial \omega_{s0}}{\partial J}\right]^2 J_0 t_1^3\right)$$

$$D_0 = J_0 \nu_{eff}$$



Block diagram of Accumulator time domain setup

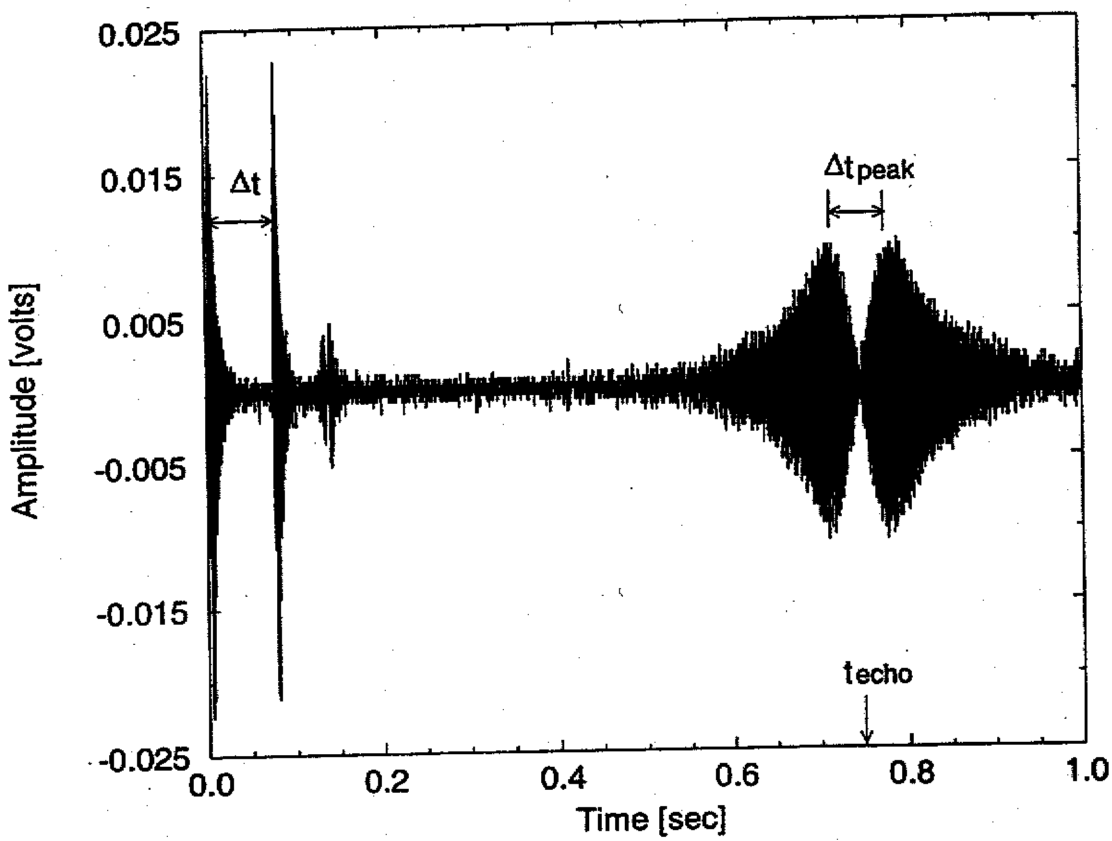


Figure 8.4: Beam response to impulse excitation at $h = 9$; followed by $h = 10$. An echo at $h = 1$ occurs centered at 0.75 seconds after the initial impulse. The beam parameters were: beam current $I_0 = 147$ mA, $\eta = .023$, total beam energy $E_0 = 8696$ MeV, beam energy spread obtained from Schottky pickup $\sigma_\epsilon = 3.2$ MeV, transverse normalized emittances $\epsilon_H = 1.75\pi$ mm-mrad, $\epsilon_V = .56\pi$ mm-mrad, and peak separation of the echo $\Delta t_{peak} = .07$ sec. Note the presence of a higher-order echo immediately following the second excitation pulse.

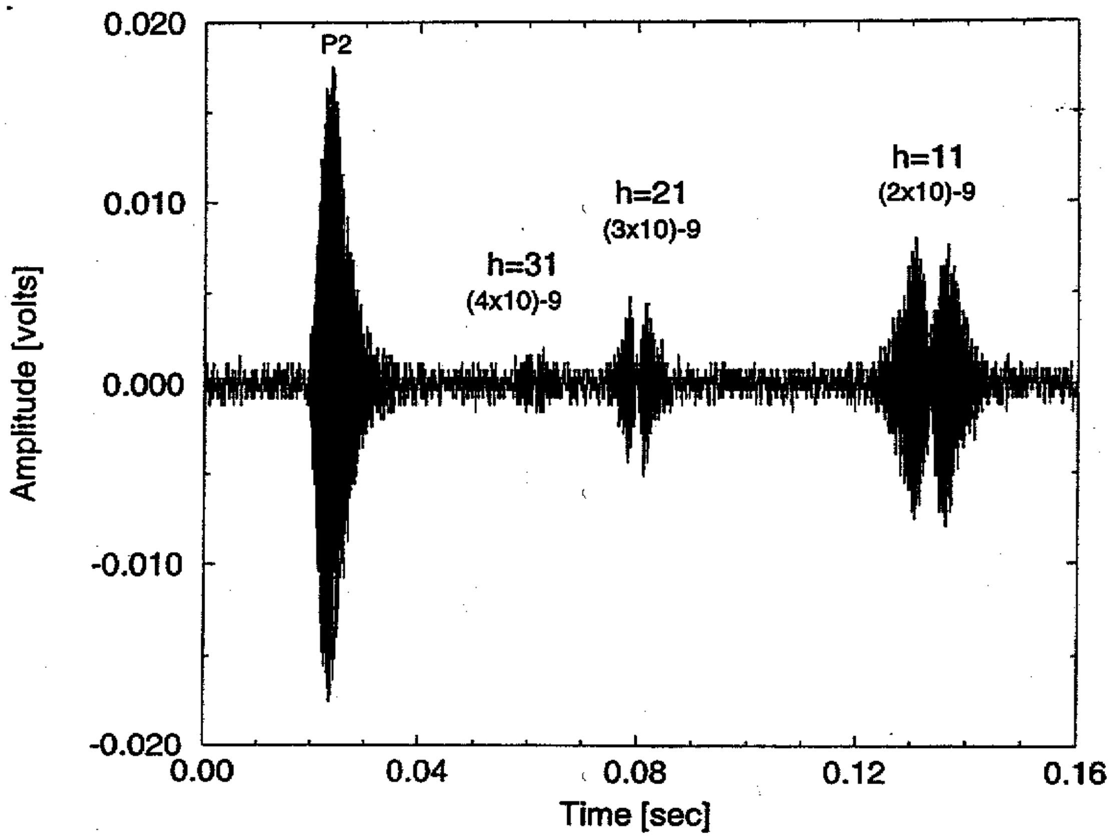
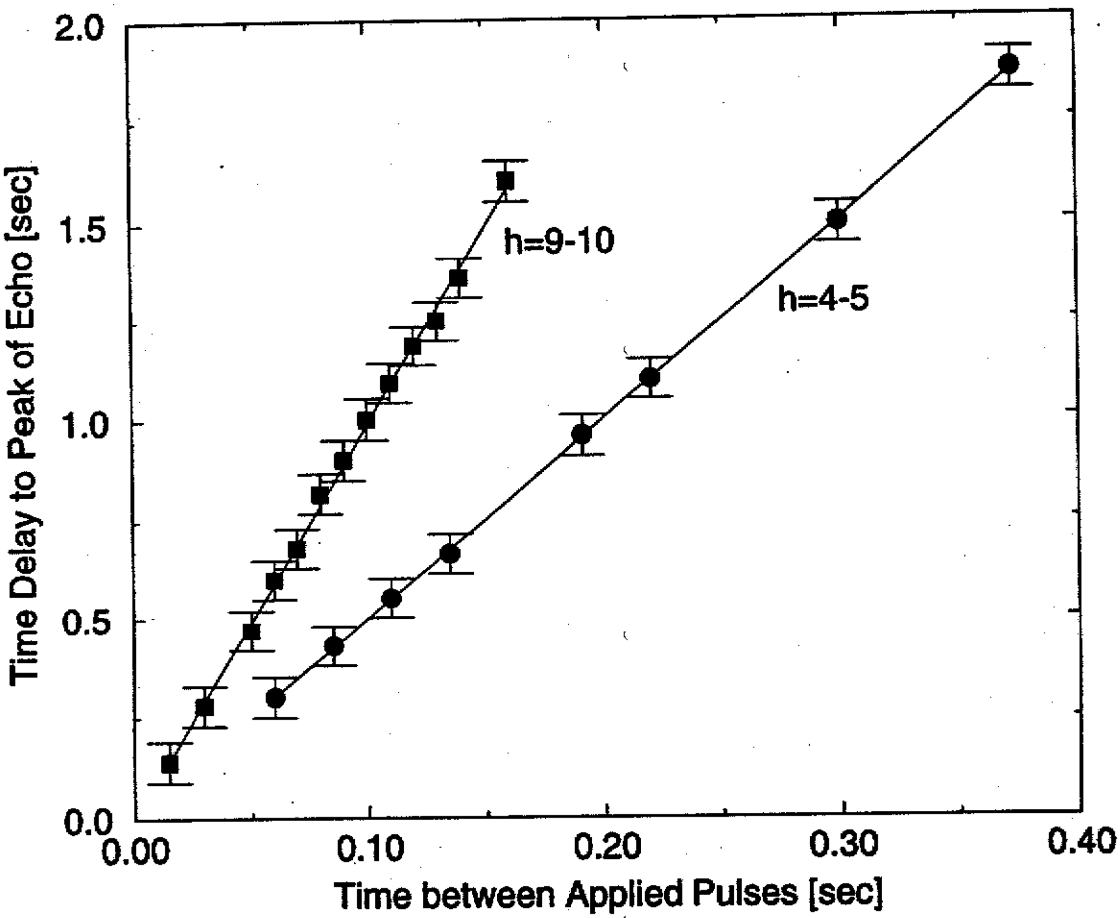


Figure 8.6: Higher order echoes. The leftmost and largest peak is the beam response to the second drive pulse. The other peaks are echoes at $h = 31$, $h = 21$ and $h = 11$. The echo at $h = 31$ is barely visible, but the relative timing verifies that this is also an echo. The delay between driving pulses was 139 ms, and there are $[\frac{30}{21} - \frac{40}{31}].139 = .019$ seconds between the echoes at $h = 31$ and $h = 21$.

Measured Echo Delay Times
Fermilab Accumulator



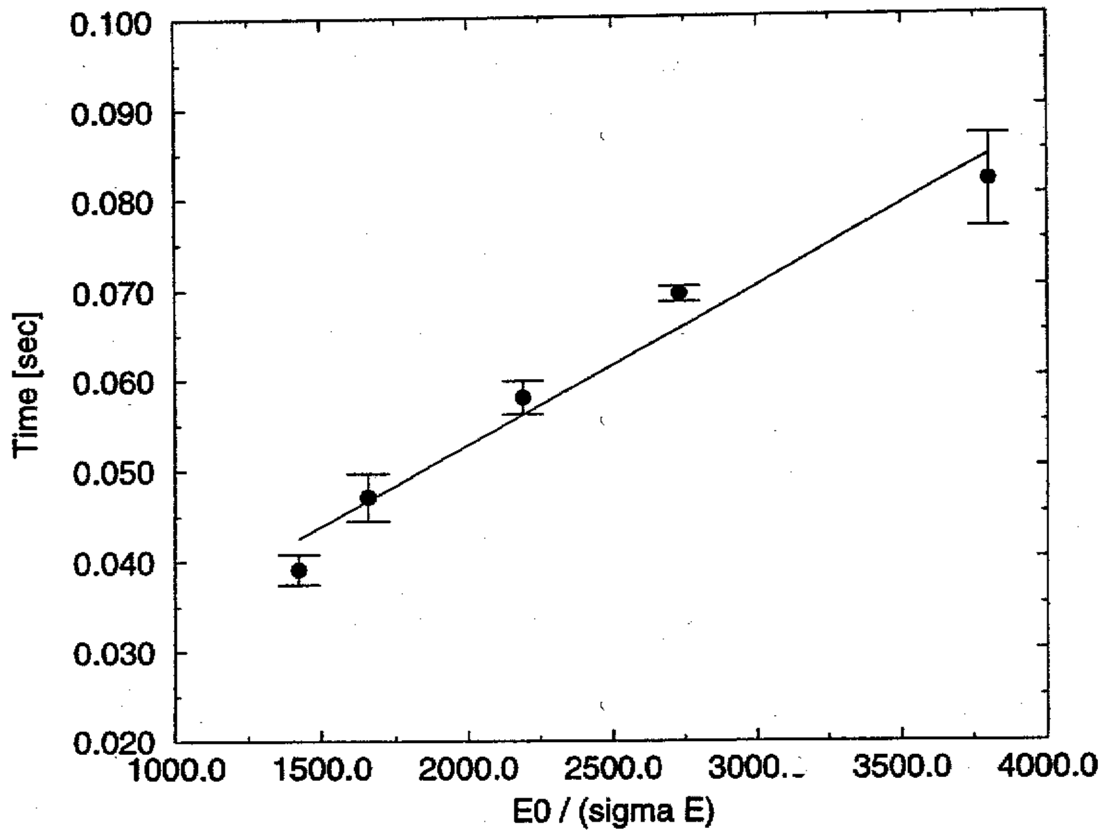


Figure 8.7: Peak separation of double-peaked echoes, Δt_{peak}, versus the inverse of $\frac{\sigma_\epsilon}{E_0}$, the energy spread of the beam. The value of the slope from the linear fit is 1.76E-5. The beam parameters were $I_0 = 147$ mA, $\eta = .023$, and $\beta^2 = .988$

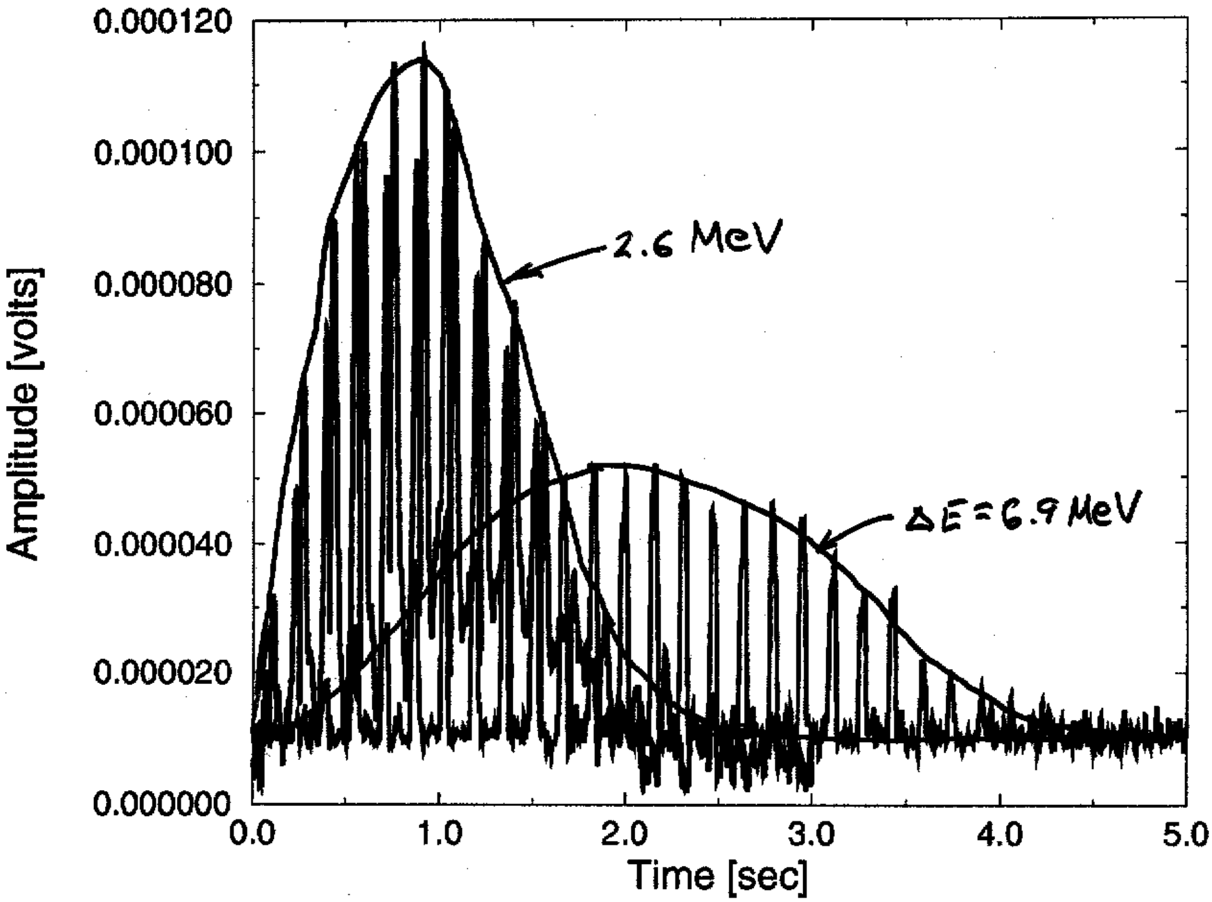


Figure 0.1: Comparison of echo scans with beams of different momentum spreads (all other parameters are the same). Red curve corresponds to $\sigma_E =$ 2.6 MeV, black curve to $\sigma_E = 6.9$ MeV.

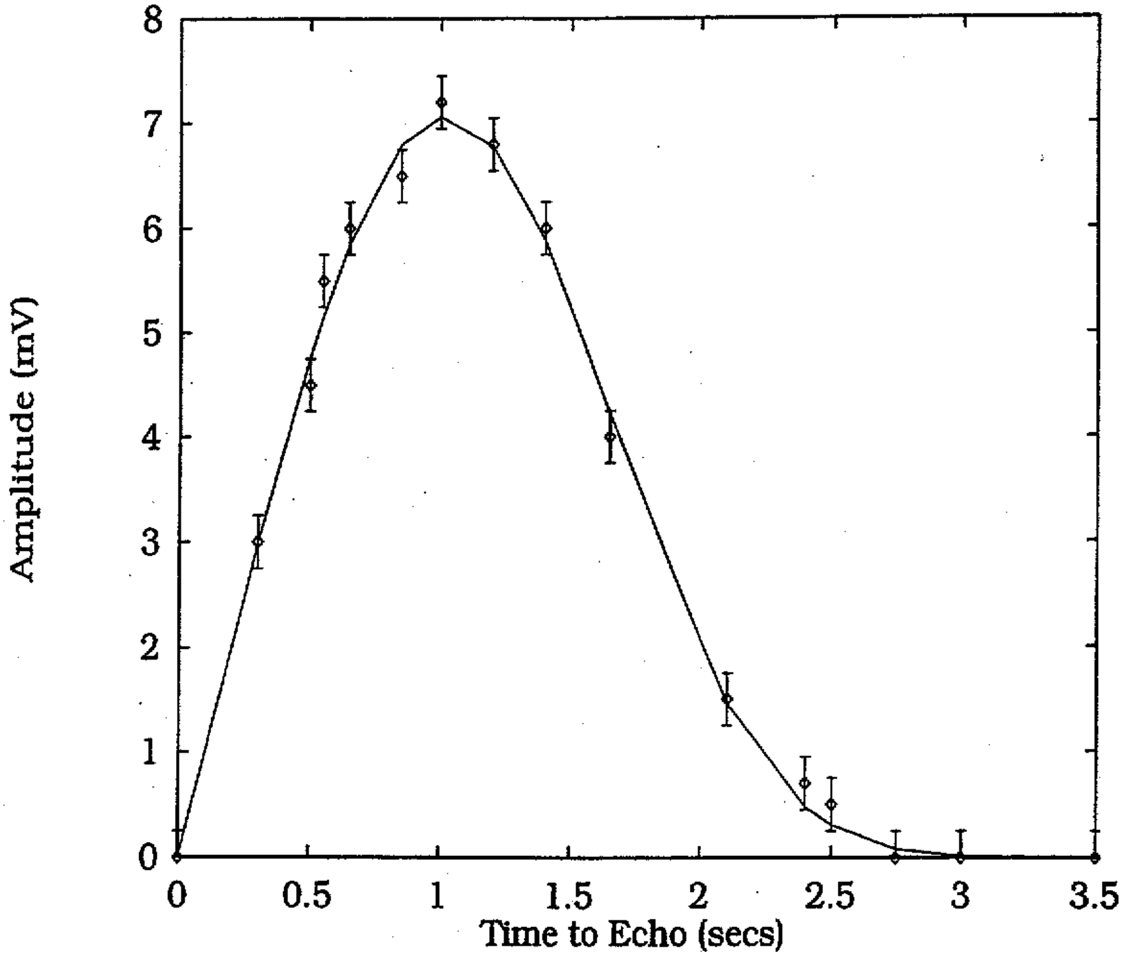


Figure 8.10: Peak echo response as a function of the time to echo following the initial pulse. The solid line represents a theoretical fit corresponding to a collision rate $\nu = (3.0 \pm 0.8) \times 10^{-4}$ Hz. The beam parameters were $I_0 = 147$ mA, $\eta = .023$, $E_0 = 8696$ MeV, beam energy spread obtained from Schottky pickup $\sigma_\epsilon = 4.0$ MeV, transverse normalized emittances $\epsilon_H = .84\pi$ mm-mrad, and $\epsilon_V = .34\pi$ mm-mrad.

SPS - CERN Brüning, et. al.

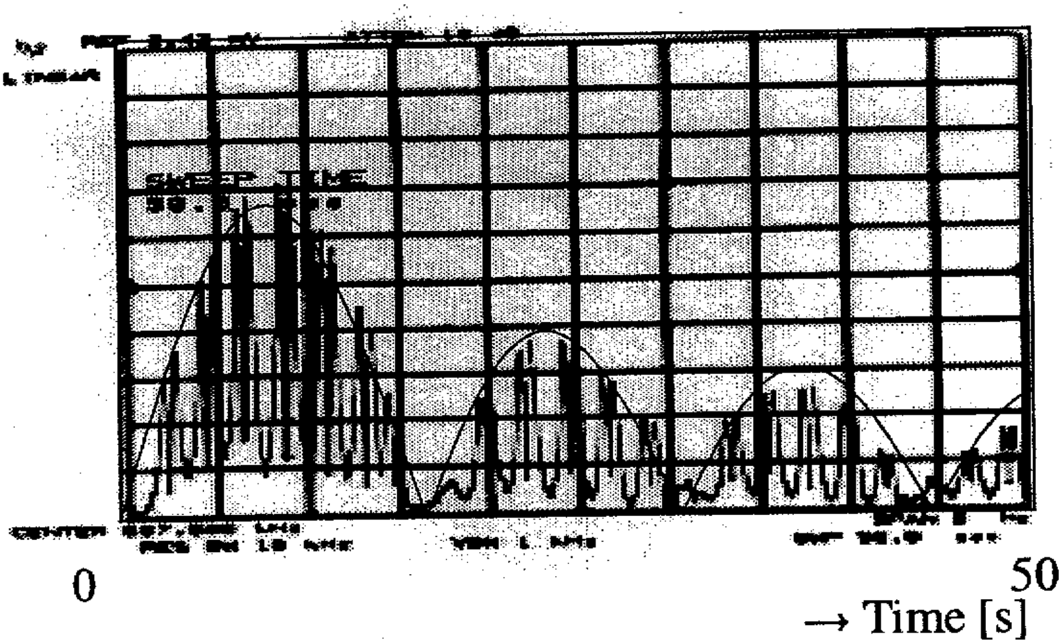


Figure 8: *The picture shows the superposition of 22 beam echos for different separation times* Δt *as a function of time after the second RF kick. The time separation of the two RF kicks varies between 5 ms and 220 ms. The solid envelope shows the analytical estimate for the maximum echo response from Equation 2 with* $D = 0$.

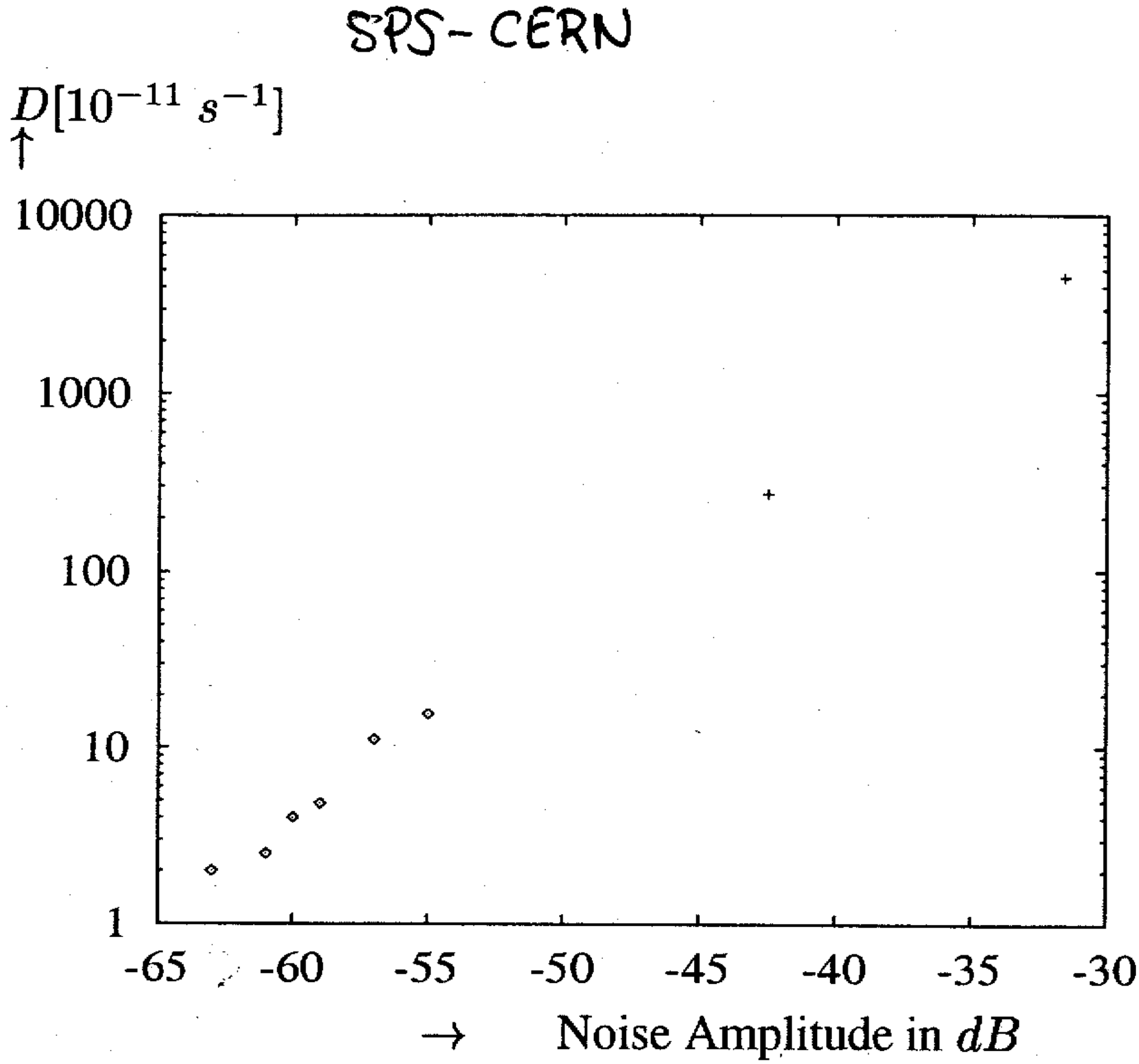
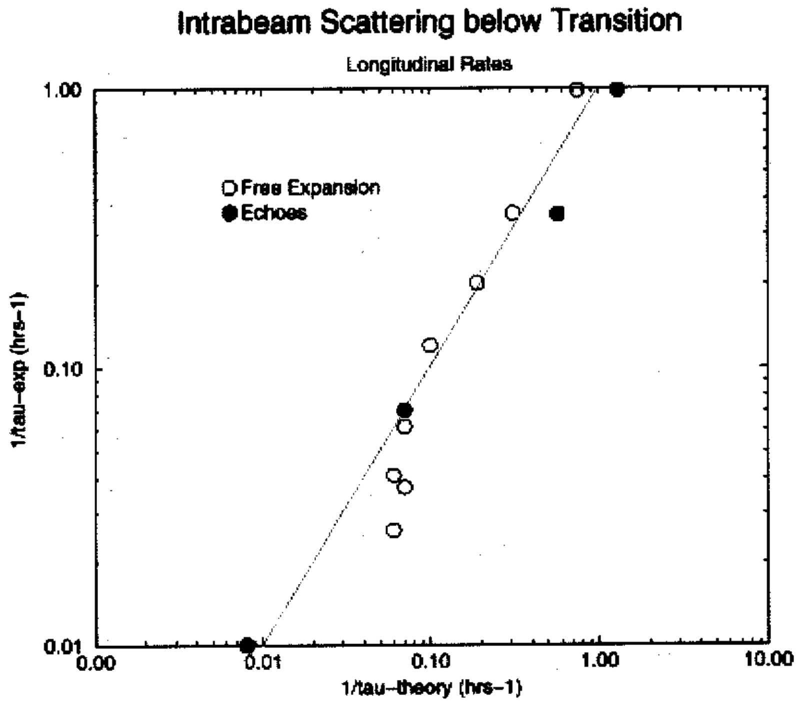


Figure 4: *Infered diffusion coefficients.*

Fermilab Antiproton Accumulator
Bhat, Spentzouris, Colestock, PAC 99



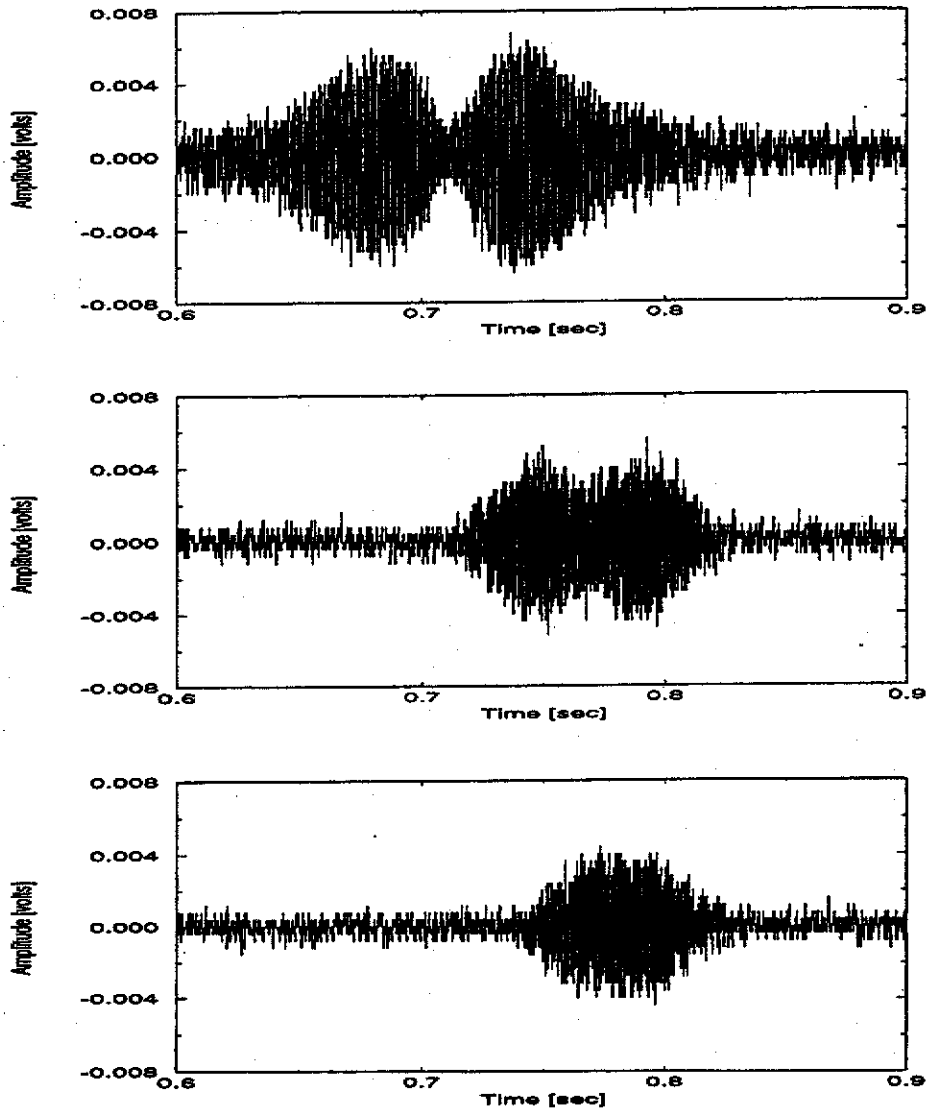


Figure 8.8: Three longitudinal beam echoes occurring in beams with different energy widths. The beam energy sigmas (σ_ϵ) were from top to bottom, 4.0, 6.1, and 8.0 MeVc. The energy spread was controlled with longitudinal stochastic cooling systems, all other beam conditions were the same. The beam intensity was 147 mA. Echoes which occurred at nearly the same time relative to the driving pulses were chosen for comparison.

CERN - SPS

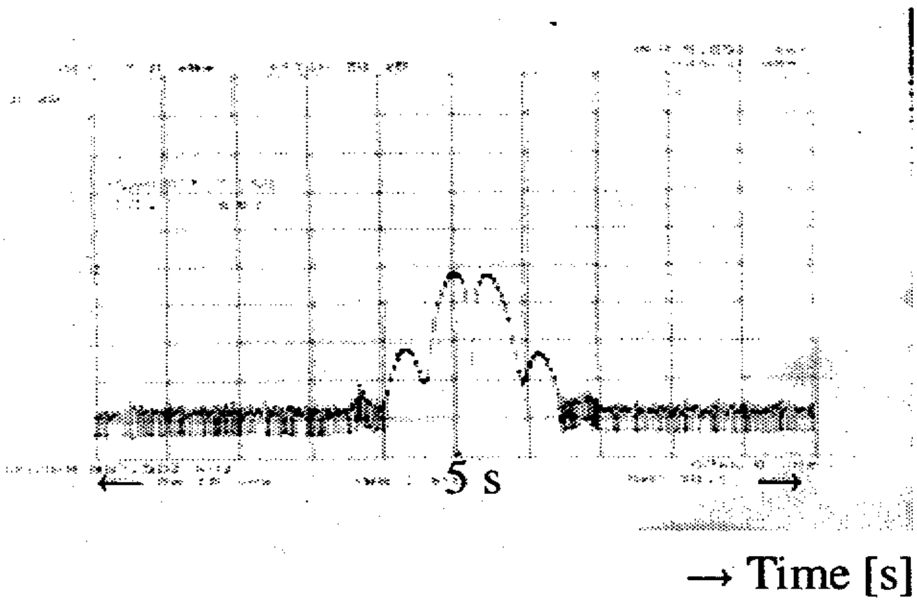


Figure 5: *The measured echo signal on a logarithmic scale. The measurement corresponds to the beam distribution in Fig. 4. One clearly recognises the multiple peaks from a non-Gaussian energy distribution.*

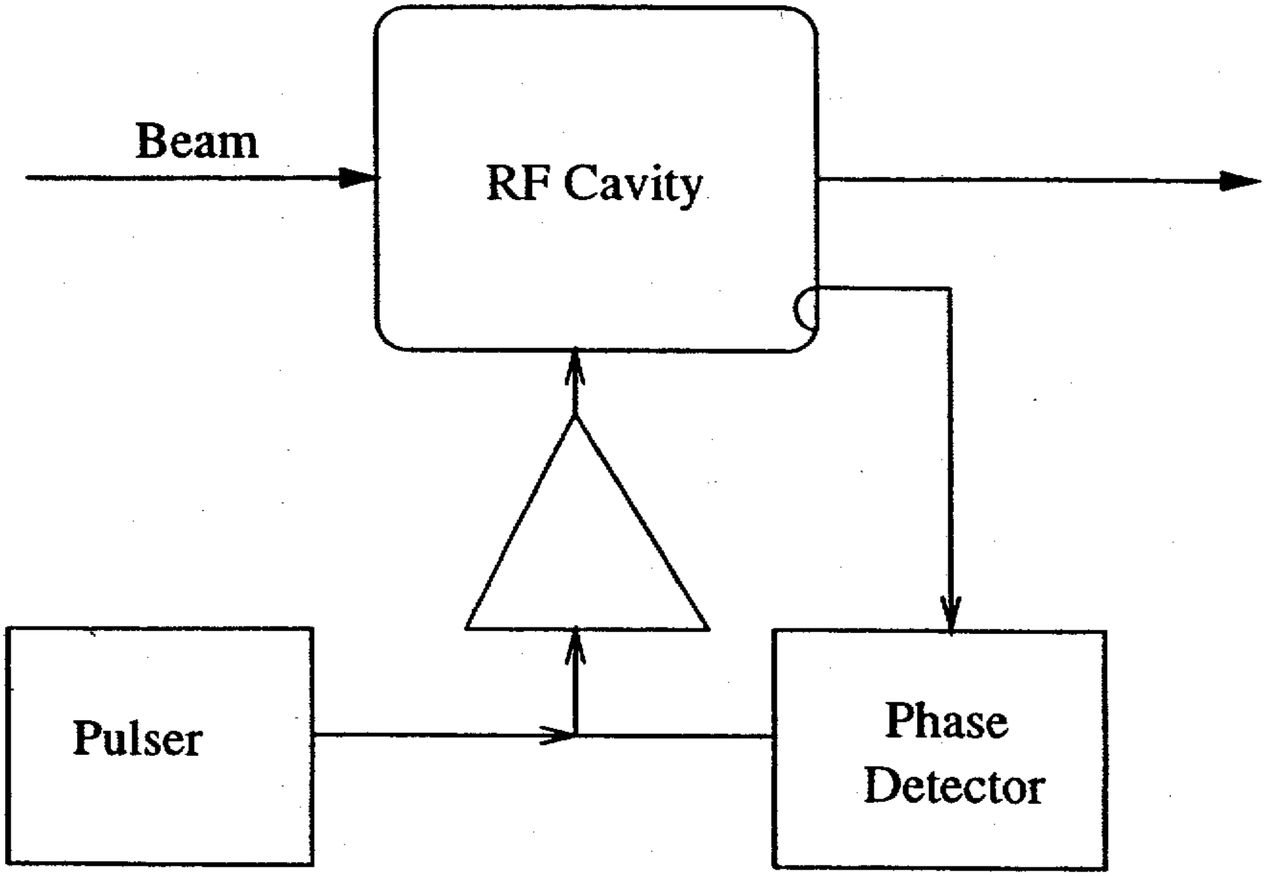
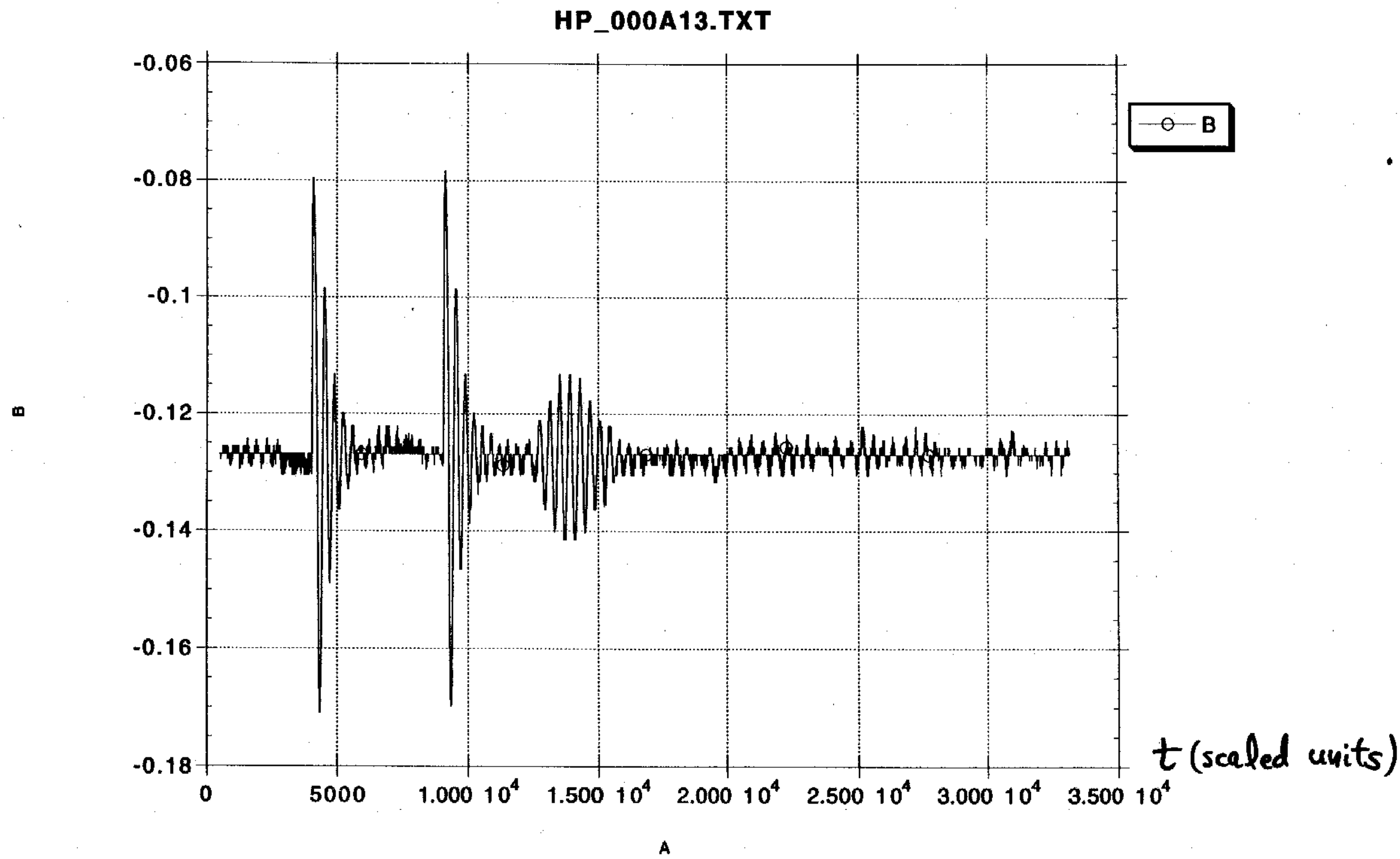
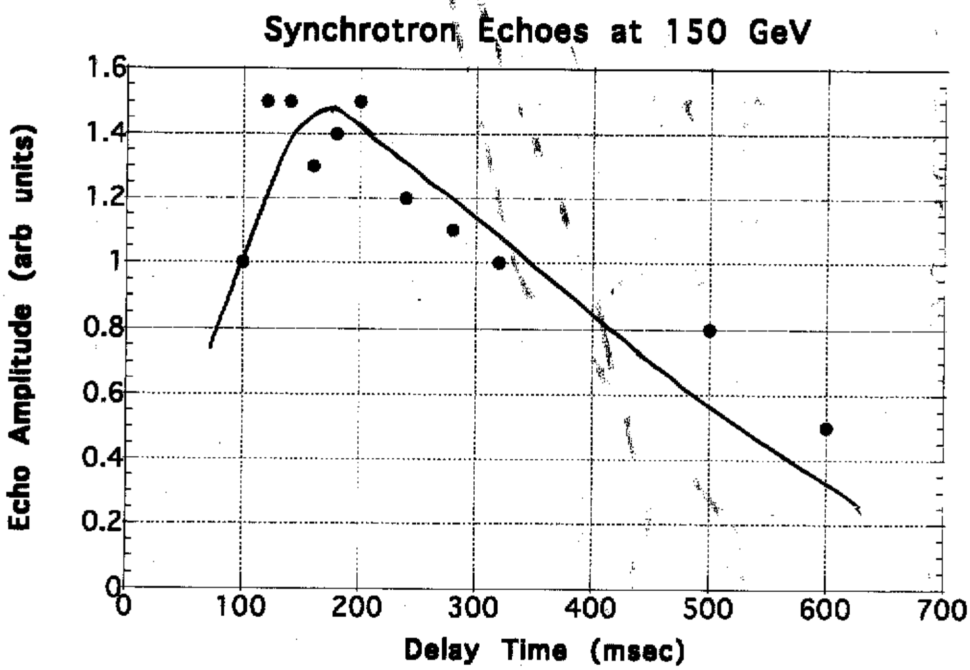


Figure 1: Sketch of the experimental setup. Successive impulses are applied with a pulser to the low-level phase feedback loop of the rf system. The resulting loop response applies a kick to the bunch energy.

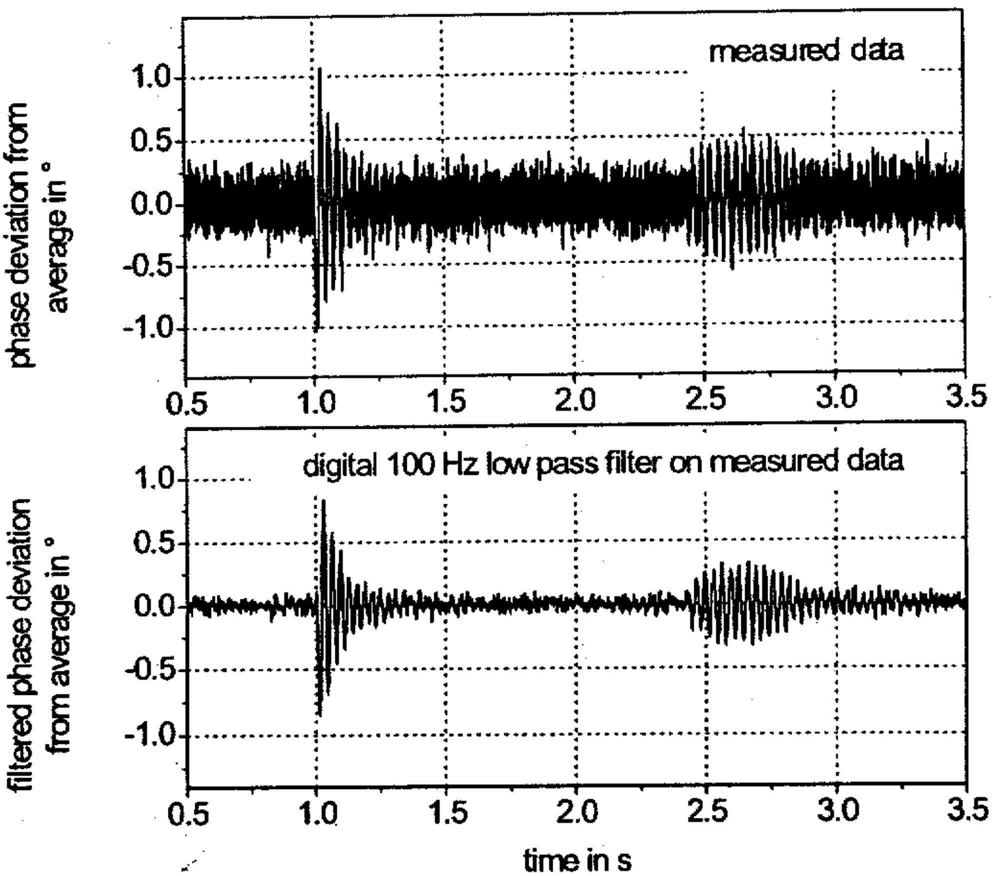
S. Assadi

Tevatron - Bunched Beam Echoes

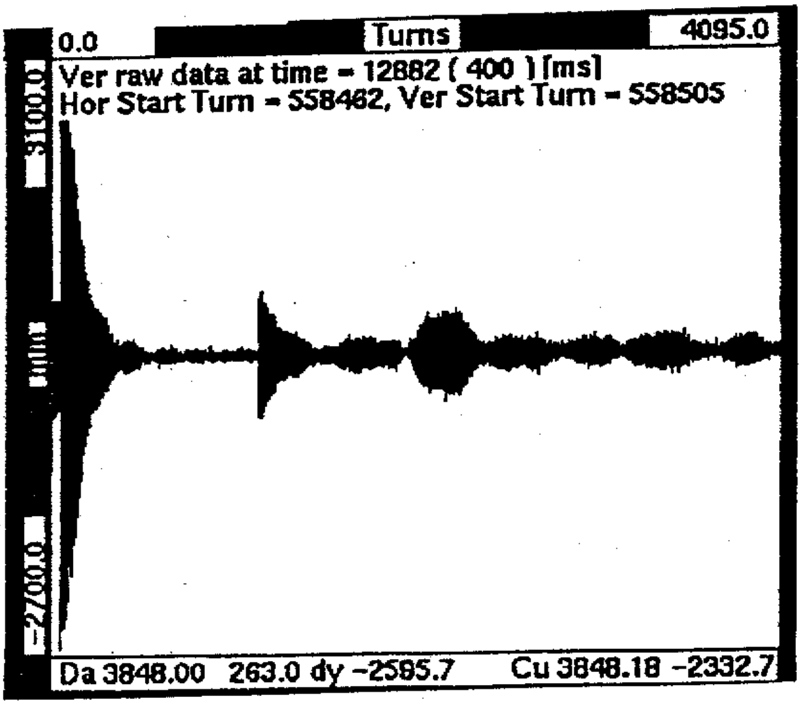



Synchrotron Echoes at 150 GeV
Echo Amplitude (arb units)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
Delay Time (msec)

HERA


measured data
1.0
0.5
0.0
-0.5
-1.0
phase deviation from average in °
0.5
1.0
1.5
2.0
2.5
3.0
3.5
digital 100 Hz low pass filter on measured data
filtered phase deviation from average in °
time in s

Transverse Echoes - CERN SPS



Issues to be explored

- Demonstrate diffusion measurements in the transverse plane
- Explore the possibility of determining the beam dielectric function with an echo
- Explore the use of echoes to measure third-order correlations
- Demonstrate transition echoes

Papers on Beam Echoes

References

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- Transverse Beam Echo Measurements on a Single Proton Bunch at the SPS
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- Effect of Diffusion on Bunched Beam Echo
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- Measuring diffusion coefficients and distribution functions using a longitudinal beam echo
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- Direct Measurement of Diffusion Rates in High Energy Synchrotrons Using Longitudinal Beam Echoes
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O. Brüning, T. Linnecar, F. Ruggiero, W. Scandale, E. Shaposhnikova and D. Stellfeld, CERN SL-MD note 206 (1996).

- Longitudinal echo in a continuous beam (extension to more general case)

E. Shaposhnikova, CERN SL/note 96-03 (RF) (1996)

- On the longitudinal echo in a continuous beam

E. Shaposhnikova, CERN SL/note 95-125 (RF) (1995)

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- Echo Effect in Accelerators

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- Echo Effect in Hadron Colliders

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Links

- Beam Echo Measurements at CERN

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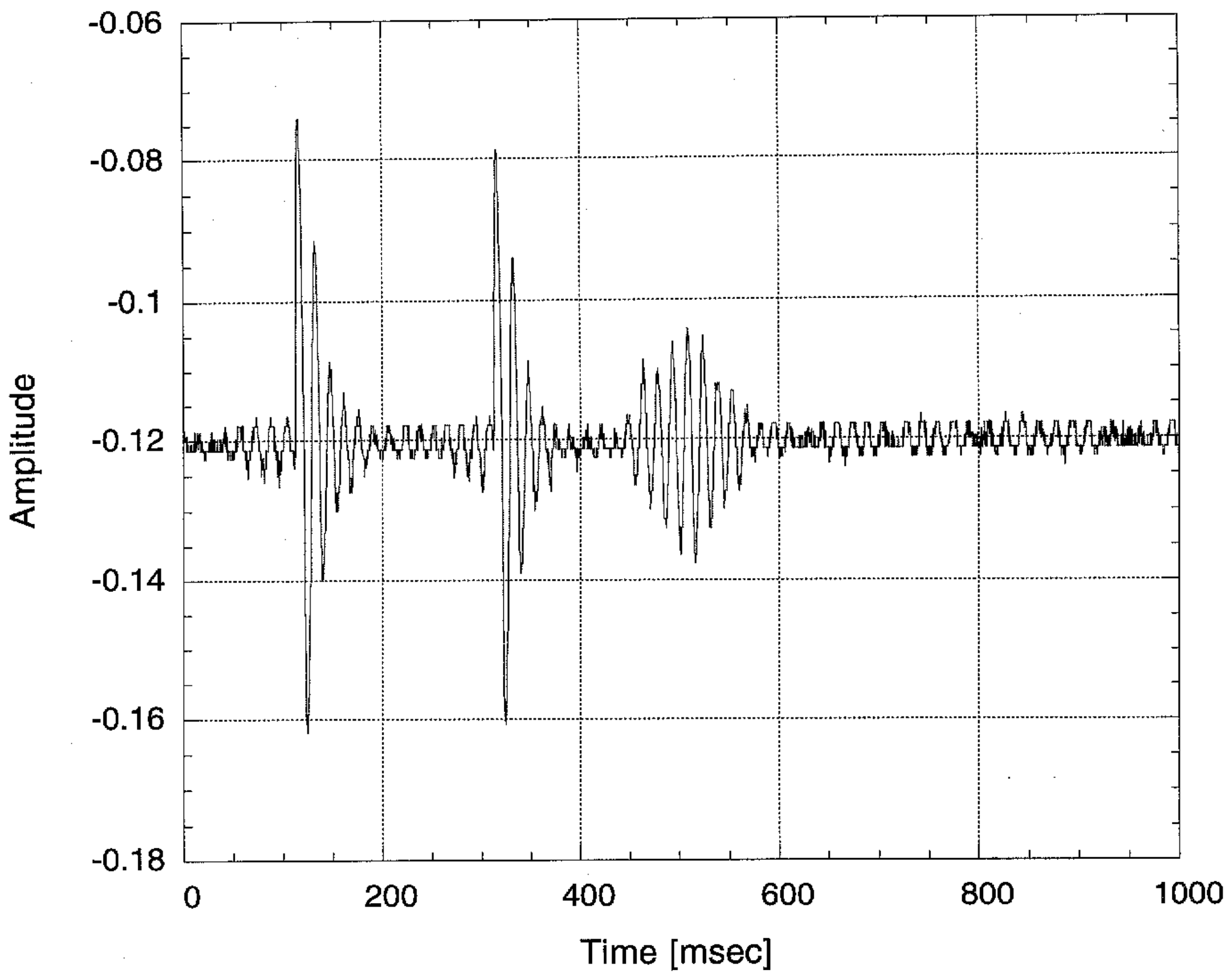
http://www.desy.de/~hoff/hoff/ECHOS/


-0.06
-0.08
-0.1
-0.12
-0.14
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Amplitude
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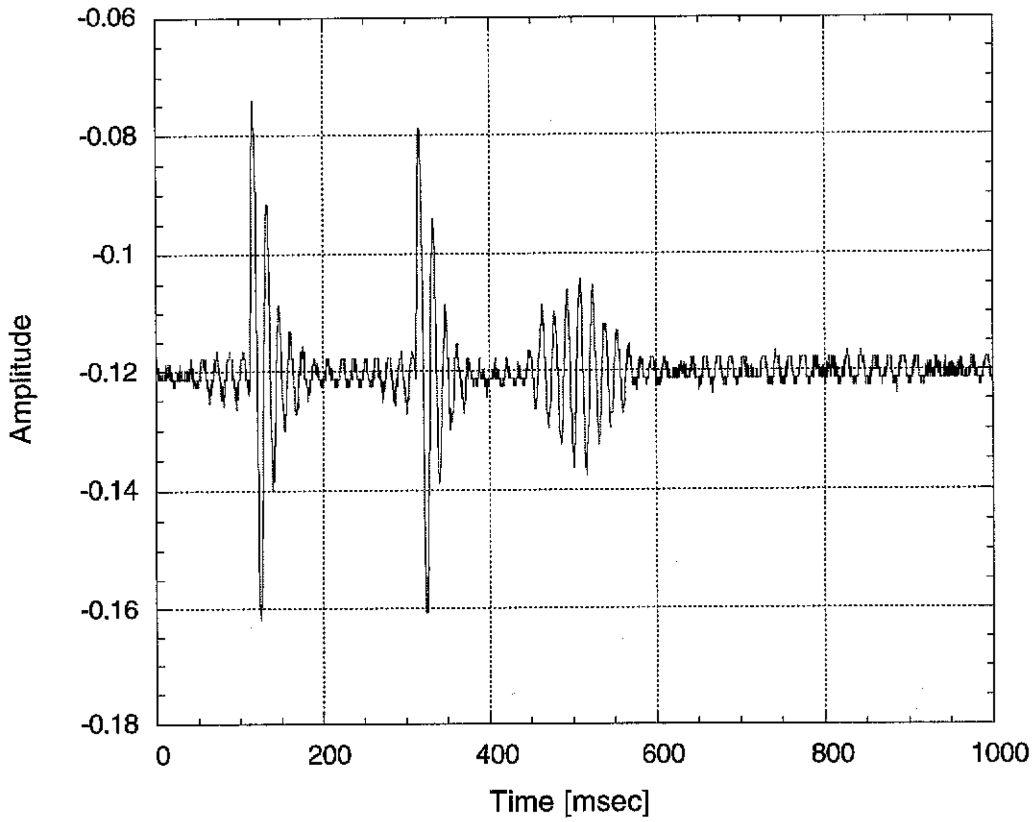
200
400
600
800
1000
Time [msec]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