Transverse echo measurements in RHIC[1]

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Abstract. Diffusion counteracts cooling and the knowledge of diffusion rates is important for the calculation of cooling times and equilibrium beam sizes. Echo measurements are a potentially sensitive method to determine diffusion rates, and longitudinal measurements were done in a number of machines. We report on transverse echo measurements in RHIC and the observed dependence of echo amplitudes on a number of parameters for beams of gold and copper ions, and protons. In particular we examine the echo amplitudes of gold and copper ion bunches of varying intensity, which exhibit different diffusion rates from intrabeam scattering.

INTRODUCTION

Beam echoes [1] are a potentially very sensitive method to measure diffusion rates. Longitudinal beam echoes were observed in several machines, and used for diffusion rate measurements [2, 3, 4]. In the SPS a transverse echo response could be observed by applying 2 dipole kicks of different strength [5]. Here we report on transverse measurements in RHIC, in which echoes were created by applying a dipole kick, followed by a quadrupole kick.

We are using the notation in Ref. [1]. After applying a dipole kick a, the beam response decoheres with time $\tau_d = T_0/4\pi\mu$, where T_0 is the revolution time and μ the the betatron tune shift at for particles at one rms beam size σ. If a second kick is applied after time τ, the dipole signal can recohere to a dipole echo η after time $\tau_{echo} = 2\tau$ (see Fig. 1 for a transverse echo in RHIC). The echo response depends on the normalized quadrupole strength $Q = \beta/f$ where β is the lattice function and f the quadrupole focal length. Second order perturbation theory predicts a time dependent dipole response [1, 6]

$$A(t) = \frac{\eta(t)}{a} = F\left(\frac{\tau_0}{\tau_d}, \frac{t-\tau_{echo}}{\tau_d}\right) \quad \text{with} \quad F(x,y) = \frac{x}{[(1+x^2-y^2)^2+4y^2]^{3/4}} \qquad (1)$$

where $\tau_d = T_0/4\pi\mu$. The relative echo amplitude $A_{max} = \eta_{max}/a$ is reduced with diffusion, and echo measurements can therefore be used to infer diffusion rates. The time of an echo measurement is considerably shorter than the time needed to observe the expansion of the beam size due to diffusion, and is also much less dependent on a precise emittance measurement. For $\tau_0 \ll \tau_d$ and small dipole kicks a the maximum echo response η_{max} was calculated as a function of a constant diffusion coefficient D_0 in Ref. [7]. This formula was found to be not applicable in the experimental parameter range reported here [8].

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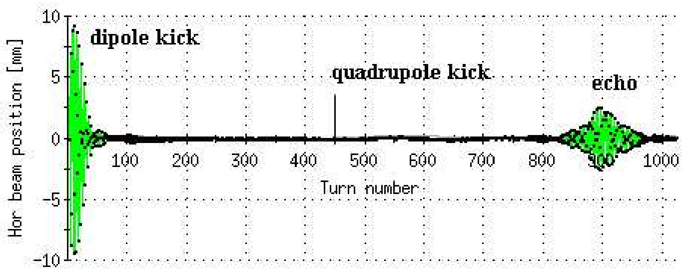


FIGURE 1. Transverse echo of a gold ion beam in RHIC. The beam is injected under a horizontal angle. After 450 turns a quadrupole kick is applied. The transverse echo appears after 900 turns.

MEASUREMENTS

A dipole kick is created by injecting the beam under a horizontal angle, leading to oscillations of about 10 mm, or 4 σ (see Fig. 1). In about 100 turns the dipole signal decoheres due to lattice nonlinearities, created by arc octupoles. After some time τ, a one-turn quadrupole kick is applied, and an echo is observable at time $\tau_{echo} = 2\tau$. Typical parameters relevant to the measurements are shown in Tab. 1 for three different ion species.

The echo amplitude was observed under variation of a number of parameters: the dipole kick amplitude a, the quadrupole kick amplitude Q, the detuning μ, the quadrupole kick time τ, the horizontal tune Q_x, and the bunch intensity N_b. Echoes could only be observed with dipole kicks of a few σ, nonlinear detuning μ an order of magnitude larger than the natural detuning, and quadrupole kick times τ no larger than a few hundred turns. The observed echo amplitudes were not sensitive to small changes in the dipole amplitude, or the horizontal tune, and proportional to the quadrupole amplitude [8]. Large chromaticity or coupling can reduce the echo signal. Operation near a strong resonance leads to particles trapped in island, which created a non-decaying non-zero dipole moment.

We show the echo amplitudes for variations in μ (Fig. 2), τ (Fig. 3), and N_b (Fig. 4)

TABLE 1. Typical parameters for transverse echo measurement in RHIC with beams of gold and copper ions, and protons.

parameter	unit	Au	Cu	p
mass and charge number A, Z	...	197, 79	63,29	1,1
relativistic γ	...	10.5	12.1	25.9
revolution time T_0	μs		12.8	
rms emittance, unnorm. ε	mm·mrad	0.16		0.10
detuning μ	...		0.0014	
decoherence time τ_d	turns		57	
dipole kick a	mm / σ		10 / $\approx$ 4	
normalized quadrupole kick Q	...		0.025	
time τ_0	turns		10	
quadrupole kick time τ	turns	450		200
synchrotron period T_s	turns	450	540	3900
bunch intensity N_b	10^9	0.1–1.0	0.1–1.3	65–95

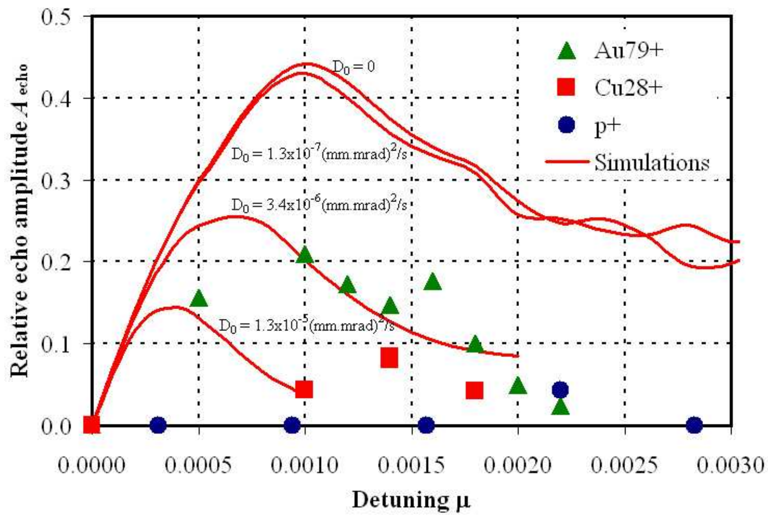


FIGURE 2. Relative echo amplitude A_{echo} as a function of the nonlinear detuning μ for bunches of gold and copper ions, and protons. For all species the quadrupole kick time was $\tau = 450$ turns. The simulations are for different diffusion coefficient for the normalized emittance. Gold data are from Ref. [8].

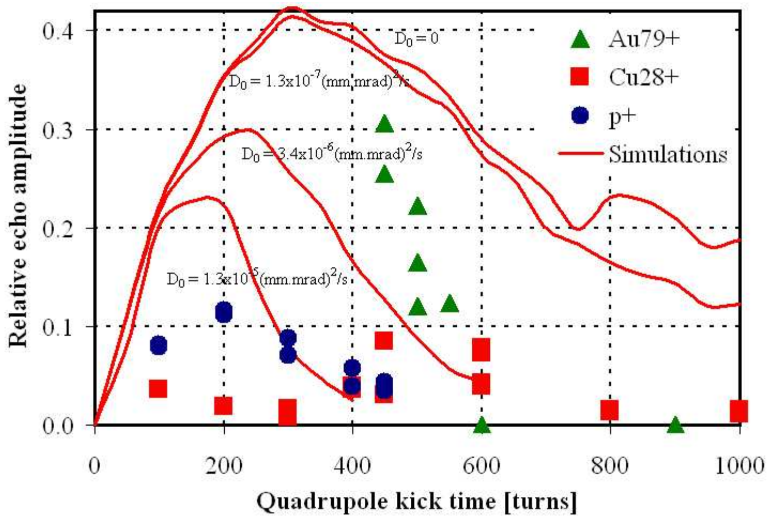
for gold and copper ions, and protons. The detuning μ was changed with arc octupoles. μ is calculated with a SixTrack [9] model of RHIC, and its value is consistent with the observed decoherence time (see Tab. 1). Without additional octupoles, no echoes can be observed. For gold and copper ion beams, the echo amplitude A_{echo} increases with increasing octupole strength reaches a maximum in the range $\mu = 0.010 - 0.015$. The amplitude falls off with further strength since the phase memory time of the particles in the transverse distribution is reduced. For protons only one weak echo is observed agains a rather large background from particles trapped in islands.

The relative echo amplitude as a function of the quadrupole kick time τ is shown in Fig. 3. For gold and copper beams the echo amplitudes were largest around 500 turns, for proton beams around only 200 turns, indicating a stronger transverse diffusion mechanism. The octupole strength for all these measurements was the same, which implies a 50% larger μ for p bunches.

Fig. 4 shows the echo amplitude as a function of the bunch intensity for gold and copper ions. For both ion species the echo amplitudes are reduced for larger bunch intensities, consistent with intrabeam scattering as the dominant diffusion source. Proton data over a sufficiently large range of N_b are not available for the same μ and τ.

SIMULATIONS

The particle motion was simulated in one dimension only, with a model that consisted of linear transfer maps, and three octupoles to adjust the nonlinear detuning. The octupoles were spaced such as to minimize resonance driving. 10000 particles were placed with an offset to simulate the dipole kick, tracked for the time τ, received a quadrupole kick, and tracked for at least another time τ. The dipole moment of the distribution is calculated turn-by-turn to obtain the relative echo amplitude. Diffusion is introduced through random kicks to the particle momentum after each turn. The random kicks



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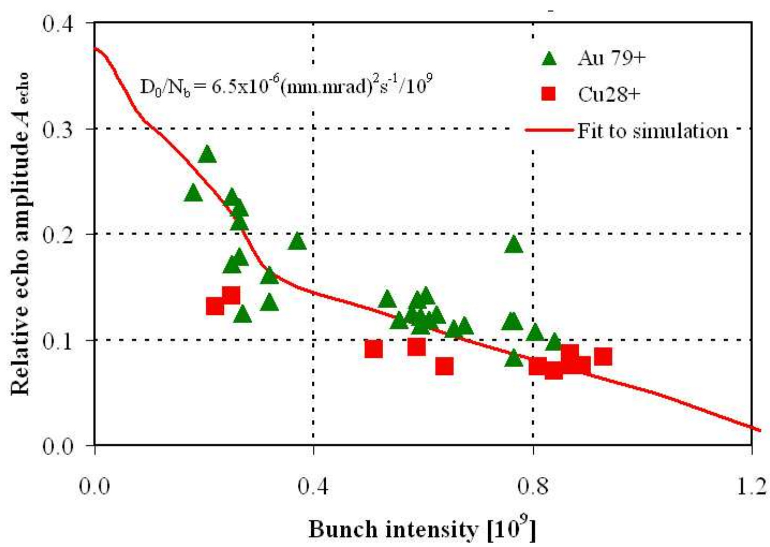

FIGURE 4. Relative echo amplitude A_{echo} as a function of the bunch intensity with $\mu = 0.0014$ and $\tau = 450$ turns. The coefficient D_0/N_b was chosen so that the simulated echo amplitudes fit the observed ones. Gold data are from Ref. [8].

follow a Gaussian distribution with a width that is constant for the whole phase space[2].

In Fig. 2 simulated curves for different diffusion coefficients are shown. For small diffusion coefficients and large detuning a significant number of particles are trapped in islands, leading to echo amplitudes that fall only slowly with increasing detuning

[2] Simulations using a width growing exponentially with action did not show significantly different qualitative results.

μ. For the gold data, the shape of the experimental data can be approximately reproduced with a constant diffusion coefficient for the normalized emittance of $D_0 = 3.4 \times 10^{-6}$ (mm mrad)^{2}s^{-1}.

Fig. 3 shows the simulated echo amplitudes as a function of the quadrupole kick time τ for varying diffusion coefficients. The weak copper ion echoes, and the fact that no gold ion echoes were observed for small quadrupole kick times is not reproduced by the simulations. However, the simulations indicate that protons exhibit stronger transverse diffusion than the heavier ions.

In Fig. 4 shows a fit to the simulated data that translates an increasing bunch intensity linearly into an increasing diffusion rate. The diffusion rate of $D_0 = 6.5 \times 10^{-6}$ (mm mrad)^{2}s^{-1} for bunches of 10^9 ions corresponds to an emittance growth time of about 100 h, the same order of magnitude that was measured observing the free expansion of bunches [10]. Note that the density of kicked beams is reduced, and that intrabeam scattering growth rate (Z^2/A) of copper ions is about a factor 2 smaller than the growth rate of gold ions.

SUMMARY

Transverse echoes were observed in RHIC at injection, with beams of gold and copper ions as well as protons. The echo amplitude was recorded as a function of detuning, quadrupole kick time, and the bunch intensity. The measurements were compared with simulated echo amplitudes, allowing the extraction of diffusion rates. The measurements revealed stronger transverse diffusion for protons than for heavier ions, indicating that a diffusion mechanism other than intrabeam scattering is dominant in for protons. For gold and copper ions the measured diffusion rates decrease approximately linearly with increasing bunch intensity, consistent with intrabeam scattering as the dominant diffusion source.

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