COHERENT SPACE CHARGE TUNE SHIFT MEASUREMENTS IN THE LOS ALAMOS PROTON STORAGE RING*

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Abstract

The coherent space charge tune shift describes the average frequency shift experienced by particles due to the effects of the beam's image charge and current and is proportional to the instantaneous beam current. For long beam pulses like the 290 ns long accumulated beam bunch in the Los Alamos Proton Storage Ring (PSR), we can observe the change in the coherent space charge tune shift longitudinally along the pulse. We measure an asymmetric betatron tune profile about the bunch center even though the beam current profile is symmetric about the peak intensity. In addition, we observe the coherent space charge tune shift to vary as a function of turn during a store. Quality measurements of the coherent space charge tune shift may provide a unique handle on interesting physics including wake field effects and electron cloud (EC) buildup. We digitize the vertical sum and difference signals from a beam position monitor, stack the digitized vector turn-by-turn, and fit the tune for each slice (0.5 ns digitization bin) along the pulse after a single-turn vertical kick. We compare the difference between the measured/fitted tune and the measured bare tune with the theoretical tune shift and infer a charge neutralization, which we relate to the EC density along the pulse and buildup in turn number.

INTRODUCTION

The coherent space charge tune shift (measured tune − bare tune) is due to image charge and current effects[1, 2],

$$\Delta\nu_y = -\frac{r_p N}{\pi\beta^2\gamma}\left[\frac{\bar{\beta}_y(\text{ring})}{2\gamma^2 B_f h^2}(1-\eta) + \frac{\pi^2\beta^2 C_2\bar{\beta}_y(\text{bend})}{24g^2}\right], \quad (1)$$

where r_p and N are the classical proton radius, number of protons, β and γ are the relativistic Lorentz factors, $\bar{\beta}_y$ is the average beta function either around the ring or in the dipoles, and B_f, h, η, C_2, and g are the bunching factor (average / peak or instantaneous current), beam pipe radius, beam neutralization, fraction of circumference occupied by dipoles, and the dipole half gap respectively. The first term in Eq. (1) describes the dependence of the coherent tune shift on the instantaneous current, while the second term relates the contribution from the average current. For the PSR, the second contributes ∼15% to the tune shift[1].

We construct a simple simulation of the coherent space charge tune shift using the model in Eq. (1) and a measured beam profile, Fig. 1. To match our measurements

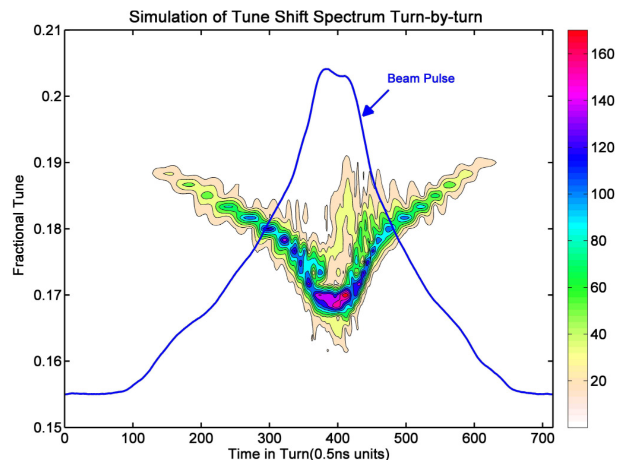

Figure 1: (Color) Simulation of tune distribution along the pulse using coherent space charge tune shift model Eq. (1) (contour) and measured longitudinal beam profile (blue line).

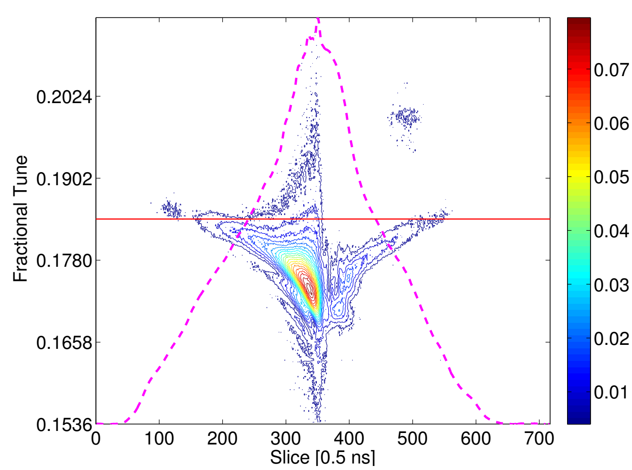

Figure 2: (Color) Measured tune distribution along the pulse (contour) and the last turn beam profile (dashed magenta line).

(described later), we divide the beam longitudinally into 0.5 ns slices. Initially the simulated beam centroid is offset transversely to produce coherent betatron oscillation, then the transverse beam centroid position is tracked for 420 turns. The FFT along turn for each slice's position yields the tune. The simulation results in a symmetric tune distribution along the bunch as expected because the beam

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profile is symmetric about the peak. Compare simulation with the measured coherent tune shift along the bunch, Fig. 2. Note that the measured tune distribution has much larger spread for slices on the leading edge than in simulation. This is because the tune for these slices is actually changing over the domain of the FFT.

From the model, we expect a symmetric tune distribution about the center of the bunch because the beam profile is symmetric about the bunch, but the measured tune distribution along the bunch is asymmetric about the bunch center. Note, the greatest discrepancy between model and measurement, particularly the magnitude of the tune FFT, occurs on the trailing edge. The difference could be due to many physical effects not included in the simple coherent space charge tune shift model of Eq. (1): EC multipactoring and neutralization, wake fields, etc. A recent study from Cornell[3] relates the coherent tune shift to beam neutralization due to the EC and changing tune shift along a train of bunches to EC build up. We will concentrate our efforts on determining the EC density.

The PSR is a harmonic one machine with only one beam bunch in the ring. For the purposes of EC buildup, the PSR beam can be thought of as a train of 100s - 1000s of bunches, so we may be able to relate changing coherent tune shift turn-by-turn to EC buildup. The PSR bunch is also a long 290 ns bunch, so we may be able to relate different coherent tune shifts along the bunch to EC density variations and gain insight into pinch dynamics and multipactoring of the EC.

MEASUREMENT AND ANALYSIS

To observe the coherent space charge tune shift, the beam must undergo coherent transverse motion, which we induce using a single-turn kick during a beam store after accumulation. The beam store is typically 200 - 400 μs. We digitize beam position and current signals at 2 GS/s (0.5 ns binning). Each digitization bin is a slice along the bunch. The digitized signal is stacked turn-by-turn such that all data for one slice is in the same row of the data matrix [# of slices, # of turns]. FFTs of data for each slice produced the contour in Fig. 2.

Hundreds of turns are required for precise frequency results from an FFT. The tune changes much faster, so we fit the position to a cosine to obtain the tune,

$$x_n = A\cos\left(2\pi\nu(n-1)+\phi\right)+O, \qquad (2)$$

where A, ν, n, ϕ, O are the amplitude, tune, turn index, phase, and offset respectively. To observe the tune change as a function of turn for each slice, we fit 30 turns. We step the domain of each successive fit by 10 turns to smooth the tune change as a function of turn. The tune fit is very good, typically yielding a fitting uncertainty $\sim 10^{-3}$.

We observe small but measurable changes in the tune as a function of turn number. Figure 3 shows the fitted tune as a function of fit number for slice 300. It is clear that we can measure a changing tune, but we are really interested in observing a change in beam neutralization.

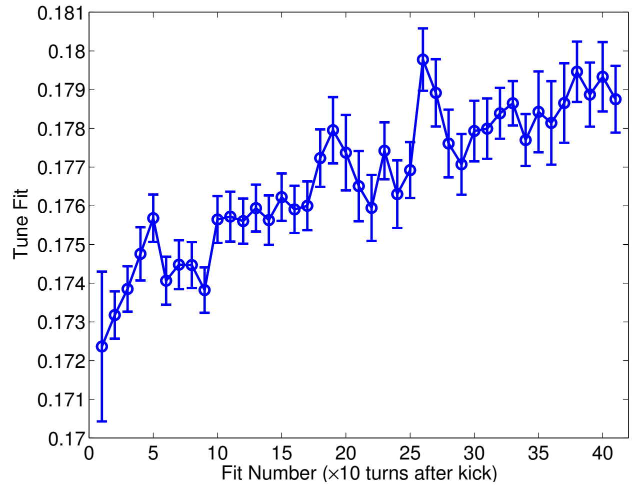

Figure 3: Fitted tune as a function of fit number (10 turn steps) after a single-turn kick for slice 300 (~25 ns in front of the peak) with one rms fitting uncertainty.

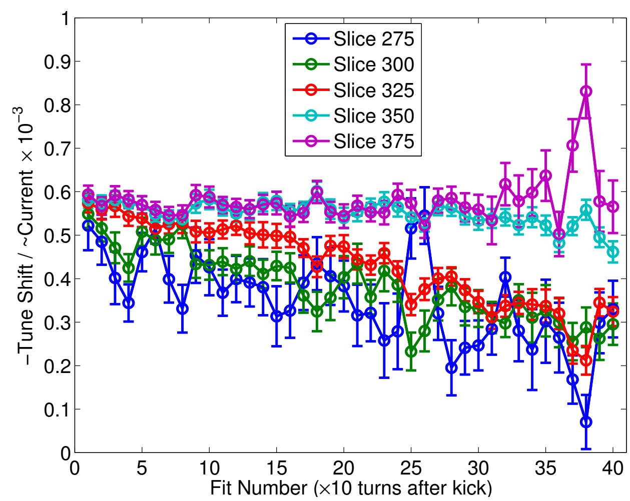

Figure 4: (Color) Normalized tune shift as a function of fit number for several slices along the bunch with one rms uncertainty. Slice 350 is the center of the bunch.

For the preliminary analysis and results reported in this paper, we note that the coherent space charge tune shift for a slice is proportional to the instantaneous current and simply normalize the measured tune shift for a slice to the average current during the fit for the slice to obtain a quantity proportional to the neutralization. If we observe the normalized tune shift measurably vary, we can conclude that the beam neutralization varies as well. We plot the normalized tune shift verses fit number for several slices in Fig. 4. The trend in the normalized tune shift is different for each time slice along the bunch. Note the normalized tune shift for slices 325 and 375, which are symmetric about the peak, has distinctly different slopes. We observe a steeper trend for slices located in front of the peak and observe lit-

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tle change in the slices on the trailing edge, which is similar to the measured tune distribution in Fig. 2.

Because the PSR bunch is a long 290 ns, in this measurement, we can also observe the measured normalized tune shift for each slice along the bunch as a function of fit number (turn number), Figs. 5 and 6.

Figure 5 plots the results for a bunched PSR production-like beam. Note the first fit after the single-turn kick yields a consistent normalized tune shift along the bunch. This is as expected if the neutralization along the bunch is constant. The structure along the bunch of the normalized tune shift is much more complicated 400 turns later. Note again the difference between leading and trailing edge. There are low frequency oscillations on the leading edge and high frequency oscillations on the trailing edge. This may be an indication of EC density variation along the long PSR bunch with EC pinch dynamics on the leading edge and multipactoring on the trailing edge.

Figure 6 plots the results for an accumulated bunched coasting beam with RF buncher off. Again, we observe for the first fit after the single-turn kick a constant normalized tune shift. Also notice the structure in the last fit, 800 turns after the single-turn kick. The spikes on the trailing edge start growing about 600 turns after the single-turn kick. Since the RF buncher is off, there is considerable beam in the gap between turns. This provides a very different beam potential that effects both EC pinch dynamics and multipactoring.

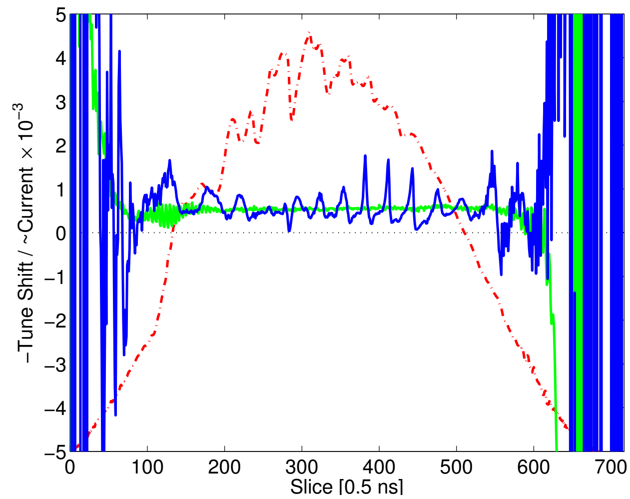

Figure 6: (Color) The measured normalized tune shift immediately after the single-turn kick (green) and 800 turns later (blue) as a function of slice along the bunch for bunched coasting beam with RF buncher off and the last turn beam profile (red).

CONCLUSIONS

We measured the coherent space charge tune shift in the PSR. We digitized beam position and current signals at 2 GS/s, where each 0.5 ns digitization bin constitutes a slice longitudinally along the beam, stacked the beam signal turn-by-turn, and took an FFT along position for each slice to obtain the tune. We induced coherent transverse motion with a single-turn kick during a beam store after accumulation. We compared model and simulated tune distributions along the pulse and found the measured tune distribution was asymmetric about the peak even though the beam profile was symmetric.

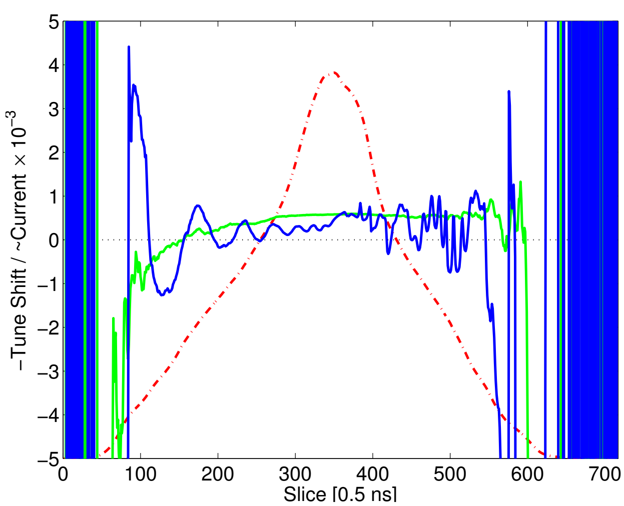

Figure 5: (Color) The measured normalized tune shift immediately after the single-turn kick (green) and 400 turns later (blue) as a function of slice along the bunch for bunched production-like beam with the RF buncher on and the last turn beam profile (red).

We show the ability to measure small changes in the tune shift as a function of slices along the bunch and turns by fitting 30 turns of beam position to a cosine. When we take into account the instantaneous current, we observe a quantity proportional to beam neutralization that also varies with turn and slice along the bunch indicating EC density variations.

We have not positively identified the changing tune shift to be neutralization due to the EC. Further work to be done includes acquiring coherent space charge tune shift data at different beam intensities and bunch lengths and using Eq. (1) in the analysis to solve directly for the beam neutralization instead of simply normalizing the tune shift to the instantaneous beam current.

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