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# SIMULATION AND OBSERVATION OF DRIVEN BEAM OSCILLATIONS WITH SPACE CHARGE IN THE CERN PS BOOSTER*

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*Abstract*

As part of the LHC Injector Upgrade project, the CERN PS Booster will be required to operate at nearly doubled intensity with little allowable increase in emittance growth or beam loss. A campaign of nonlinear optics measurements from turn-by-turn trajectory measurements, with the goal of characterizing and then compensating for higher-order resonances, is planned for after Long Shutdown 1. The trajectory measurement system is expected initially to require high intensity beam in order to have good position measurement resolution, so understanding space charge effects will be important for optics analysis. We present the results of simulations of driven beam oscillations with space charge effects, and comparison with trial beam trajectory measurements.

## INTRODUCTION

Before the first Long Shutdown (LS1), trial measurements were done in preparation for nonlinear optics measurements which will take place after LS1. These trial turn-by-turn measurements of driven beam trajectories were made using prototype systems for both measurement and for beam excitation. Due to a hardware limitation that cannot be changed until LS2, we expect that in order to have good position resolution these trajectory measurements will have to be made with high beam intensity and therefore strong space charge effects.

The coherent betatron oscillations produced by AC dipole excitation were too small and irregular to allow for precise determination of the higher-order frequency components of the beam motion. In order to understand the reason for this poor beam response, we examine the effects of space charge forces on driven beam oscillations using PTC-Orbit simulations. These simulations will also be useful for understanding any effects of space charge on higher-order frequency components of the beam spectrum, in case they need to be taken into consideration for nonlinear optics calculations. We also examine the effects of tune jitter in the PSB as another factor contributing to poor beam response to the AC dipole.

## MEASURED DRIVEN OSCILLATIONS

Tests of driving coherent transverse oscillations using the PSB's transverse damper were conducted just before LS1. The measurements were made using a special study cycle with high intensity ($4 \times 10^{12}$ protons per pulse) and large normalized emittance ($\epsilon_{Nx} = 10\mu m$, $\epsilon_y = 6\mu m$), single-harmonic RF with $\delta p = 0.00163$ and $\sigma_s = 330$ ns, and an energy plateau of 160 MeV. The measurements were done both with natural chromaticity ($\xi_x \approx -3.5$, $\xi_y \approx -6.8$), and with chromaticity corrected in one plane ($\xi_x \approx -7$, $\xi_y \approx 0$).

The angular kick provided by the transverse damper kicker was estimated to be on the order of $1\mu$rad [1]. This value is only approximate because some of the amplifiers in the damper system were found to be faulty and the exact response of the system was uncertain. Upgrades to the damper system are underway, and when it is recommissioned after LS1 it will have increased power and a more precisely known angular kick strength. The beta functions at the location of the AC dipole are $\beta_x = 5.7m$ and $\beta_y = 4.1m$.

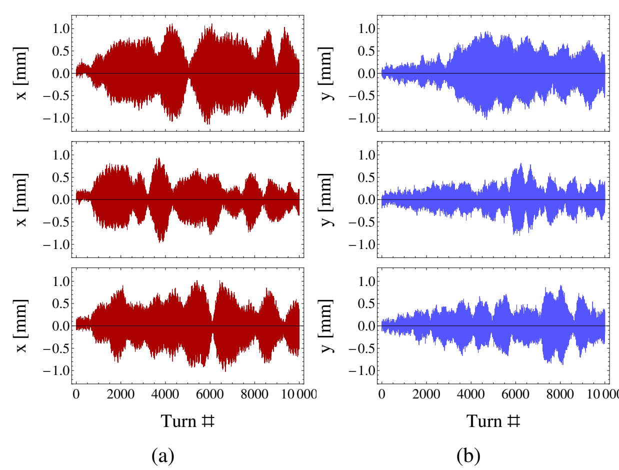


Figure 1: Measured horizontal (a) and vertical (b) beam position while driving with AC dipole in both planes, for three successive beam pulses.

The beam was excited by driving it with a constant frequency near the betatron tune in each plane, varying the driving tune in small increments to find the optimal tune for best beam response. The measured beam trajectories on three successive beam pulses, for the driving tunes which gave the largest amplitude response, are shown in Fig. 1. The largest oscillation amplitude was observed when the driving frequencies were within 0.001 of the average measured betatron tunes. However, we observed a ripple in the power supply to all of the ring's focusing quadrupoles, which caused the betatron tunes to fluctuate with an amplitude of ≈ 0.005 and a period of several hundred turns. Therefore the actual separation between natural and driving tunes varied considerably over the measurement period.

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## PTC-ORBIT TRACKING RESULTS

In order to determine any possible effects of strong direct and indirect space charge on the beam's response to AC dipole excitation, tracking simulations were carried out using PTC-Orbit [2, 3]. Three cases were examined: no space charge effects, direct space charge only, and direct plus indirect space charge. These simulations use the ideal machine lattice, with no magnet strength errors or misalignments included, and with natural chromaticity ($\xi_x \approx -3.5$, $\xi_y \approx -6.8$). In all three cases the beam was driven in the vertical plane at a tune 0.012 below the zero-intensity tune, with an angular kick of 20 $\mu$rad.

These simulations show that direct space charge effects reduce the beam oscillation amplitude by about 25%. This is likely due to the incoherent tune spread, which causes the tune of individual particles to be farther from the driving tune. In the case with both direct and indirect space charge, the oscillation amplitude is larger than in both the case with no space charge and with only direct space charge, but this is just due to the coherent tune shift, which reduces $\delta q_{AC}$ from 0.012 to 0.008. The amplitude of the beam response to an AC dipole is expected to be proportional to $sin^{-1}[\pi\delta q_{AC}]$, and in fact the response amplitude in the two space charge cases is consistent given the change in $\delta q_{AC}$.

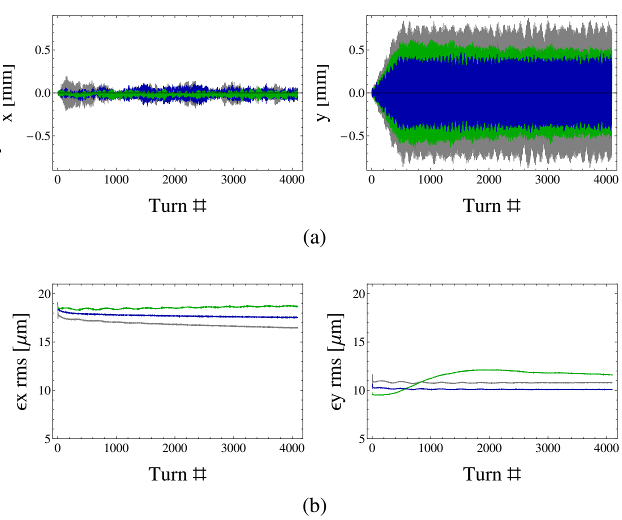


Figure 2: PTC-orbit simulation of (a) beam trajectories and (b) RMS emittance evolution with AC dipole excitation in vertical plane only. Three cases are shown: without space charge effects (green), with direct space charge only (blue), and with both direct and indirect space charge (gray).

In the PTC-Orbit simulation with no space charge some emittance growth is observed, which is presumably due to the chromatic tune spread $\Delta Q \approx 0.01$. Some particles in the bunch will have a tune very close to the driving tune, resulting in a larger amplitude excitation relative to the rest of the bunch. The inclusion of direct space charge in the model eliminates this emittance growth because the incoherent tune shift moves the tune of individual particles further away from the driving tune.

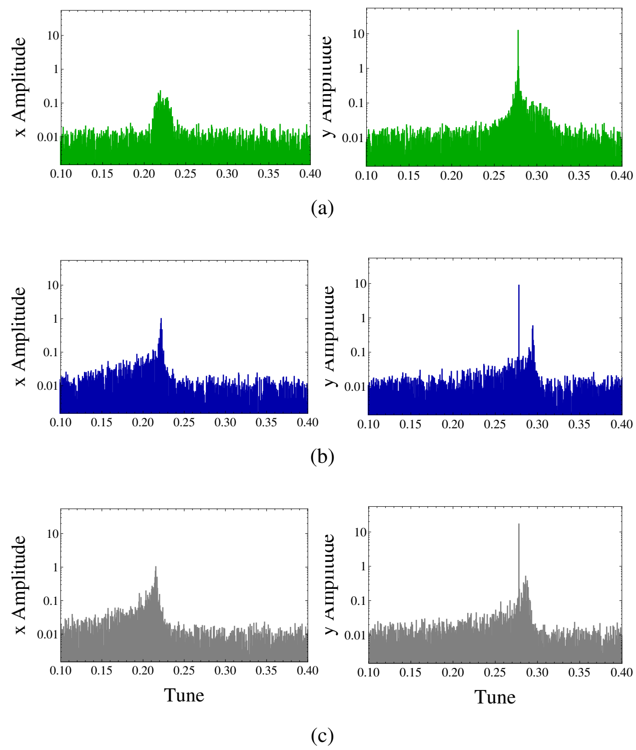


Figure 3: Spectra from PTC-orbit simulations with AC dipole excitation in the vertical plane only, (a) without space charge effects, (b) with direct space charge only, and (c) with both direct and indirect space charge.

## EFFECTS OF TUNE RIPPLE

Another likely explanation for the small response to the AC dipole is the large tune variation coupled with the small angular kick ($\approx 1\mu rad$) provided by the damper. Since the amplitude is proportional to $\theta_{AC}/sin[\pi\delta q_{AC}]$, based on the amplitude response in the PTC-Orbit simulations, we would expect to need a driving tune that is less than 0.001 away from the natural tune in order to get a reasonable oscillation amplitude from such a small angular kick.

The ripple in the quadrupole power supply causes a tune ripple that is larger than this desired driving tune separation needed to drive a large oscillation amplitude. The measured variation in quadrupole focusing strength caused by the power supply ripple and the frequency spectrum of the magnet current are shown in Figs. 4 and 5. The 1200 Hz peak corresponds to a period of 833 turns, and the amplitude of the tune shift expected from this magnitude of focusing perturbation is about 0.005. The measured tune ripple, shown in Fig. 6, is in fact similar to that predicted from the measured magnet power supply ripple.

The effect of tune ripple on AC dipole response was examined using simple tracking simulations with a variable thin quadrupole element added to each focusing quadrupole. A single particle was tracked through the idealized linear lattice, and the quadrupole strength was varied at each turn in accordance with the measured quadrupole magnet current variation. The resulting trajectories, each with random

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initial phase for the quadrupole ripple, are shown in Fig. 7. They show a similar amplitude response as the measured trajectories shown in Fig. 1.

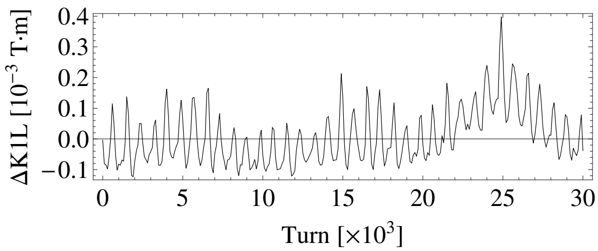


Figure 4: Variation in focusing strength corresponding to measured focusing quadrupole magnet current.

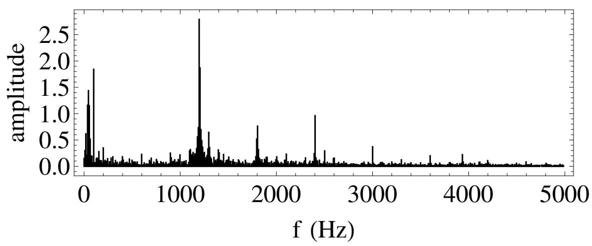


Figure 5: Frequency spectrum of measured quadrupole current, which produces a tune jitter of ≈ 0.005 with a period of 800 turns.

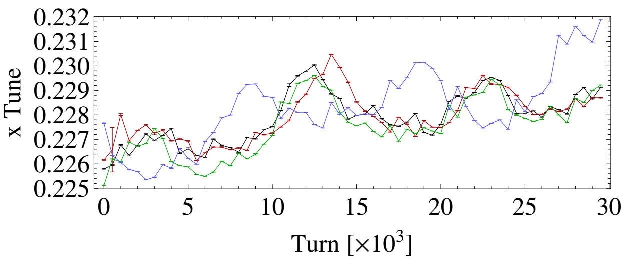


Figure 6: Horizontal tune of freely oscillating beam during four beam pulses, calculated in 500-turn increments.

## CONCLUSIONS

Simulations with PTC-orbit show that direct and indirect space charge have a rather small effect on the response of the beam to an AC dipole. Direct space charge reduces the amplitude of the response by about 25%, presumably due to the incoherent tune spread, but does not alter the typical beam envelope response. The large incoherent tune spread appears to suppress the emittance growth that would otherwise be caused by the chromatic tune spread, which may be helpful given that chromaticity cannot be corrected in both planes simultaneously in the PSB.

In these simulations with space charge, we observe that the natural coherent tune is visible in the frequency spectrum of the driven beam along with the driving tune. Further studies

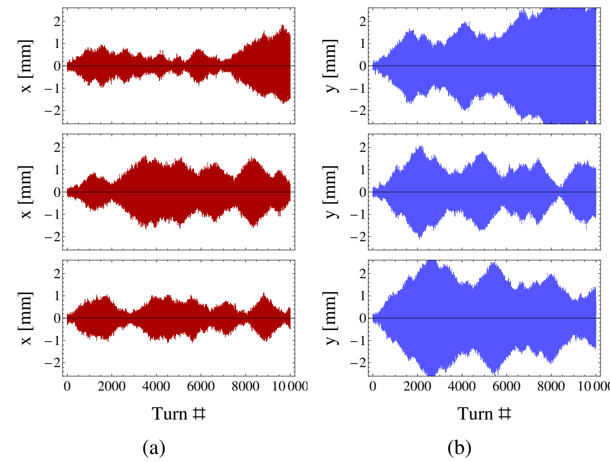


Figure 7: Trajectory from tracking simulations with AC dipole and quadrupole power supply ripple.

may be needed to determine the effects of space charge on higher-order resonance lines in the spectrum.

The betatron tune ripple in the PSB has a greater effect on the response of the beam to the AC dipole than does space charge, and it is the likely cause of the small and irregular response that was observed during trial measurements before LS1. The driving kick during these tests was weak, on the order of 1 $\mu$rad. Based on the PTC-orbit simulations we expect to need a rather small $\delta q_{AC}$ of about 0.001 in order to produce a significant beam amplitude response with such a small angular kick. A ripple in the power supply to the focusing quadrupoles causes a tune ripple of about 0.005 with a period of a few hundred turns, so it is not possible to develop a large beam oscillation under these conditions.

The cause of the power supply ripple was identified and repaired during LS1, so we can expect to see a significant reduction in the tune variability when these measurements are repeated after LS1. In addition, faulty amplifiers in the damper system have been repaired, which will at least double the available angular kick, and upgrades are underway that should increase the power of the damper system even further. With these improvements in tune stability and damper kicker strength, we may hope to see much higher amplitude beam oscillations, allowing for a precise determination of higher-order frequency components in the beam spectra.

## REFERENCES

[1] C. Carter et al., "The Transverse Feedback System for the CERN PS Booster", Particle Accelerator Conference 1981, Washington.

[2] A.Shishlo, J.Holmes, E. Forest, A.Molodozhentsev. Synopsis of the PTC and ORBIT integration. KEK Internal Report (A), 2007-4, Nov. 2007.

[3] V. Forte et al., "Investigations on CERN PSB Beam Dynamics with Strong Direct Space Charge Effects Using the PTC-ORBIT Code", WEPEA052, IPAC'13, Shanghai, China.