OBSERVATION OF COHERENT OSCILLATIONS OF COLLIDING BUNCHES AT THE TEVATRON*

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Abstract

Coherent vertical oscillations of colliding bunches in the Tevatron have been observed using a new data acquisition system. The new device allows turn by turn sampling of transverse positions of every bunch for large number of turns at any time during an HEP store. Experimental observations of coherent beam-beam modes are presented along with a simplified theoretical model.

INTRODUCTION

Currently there are no indications of beam-beam driven coherent instabilities during the operation of the Tevatron collider. However, a number of times special conditions were created which caused multi bunch coherent oscillations to grow and eventually quench the machine [1]. This instability may be related to the interplay between coherent beam-beam effects and machine impedance [2]. Beam dynamics in the system of many colliding bunches can be studied using a numerical simulation, and a number of codes are being developed to accomplish this task [3]. However, experimental observation of coherent beam-beam modes at an operating collider would provide valuable data for the development of modeling and for operation of future machines.

Since 2007 the Tevatron operates with essentially equal head-on beam-beam tune shifts for protons and antiprotons [4]. The total beam-beam parameter for both beams currently reaches 0.024. With 36 bunches per beam, 2 head-on and 136 long range collision points (two beams in the same vacuum chamber), a large variety of coherent beam-beam modes can be expected to be seen in the spectrum of dipole oscillations of individual bunches.

To measure the turn by turn vertical centroid positions of individual bunches, a new system has been devised based on a single beam position monitor and a fast oscilloscope.

This report presents the basic parameters and limitations of the measurement system. Results of the first observations of coherent modes in oscillations of protons and antiprotons are shown. Lastly, a simple model based on the rigid bunch approximation is discussed.

INSTRUMENTATION

The experimental setup shown in Fig. 1 consists of variable attenuators, phase shifters, an RF hybrid, an amplifier and a fast digital oscilloscope [5]. The variable attenuators are used for compensating the beam position offset. Since the plate signals are not integrated they have to be synchronized within some 10 ps to minimize common mode and to achieve submicron position resolution. The plates of the VB11 BPM were chosen as a pickup because of the large vertical beta function at that location that translates into better S/N ratio.

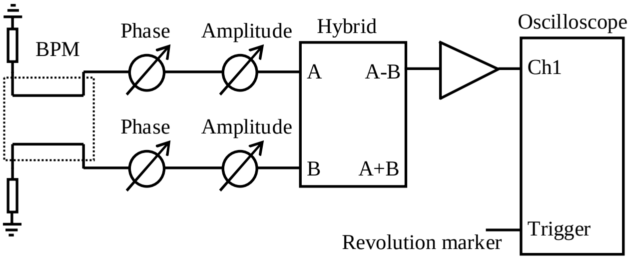

Figure 1. Block diagram of the measurement setup.

After careful adjustment of phases and amplitudes the hybrid provides about 44 dB of common mode suppression. To effectively use the dynamic range of the oscilloscope we amplified the difference signal by about 25 dB for protons and 33 dB for antiprotons.

Challenges

The pickup used is a directional stripline with cables connected to both sides of the electrodes. So both the proton and the antiproton signals can be acquired from the same pickup. However, with 26 dB directivity both the proton and the antiproton signals are always present at both ends of the pickup, see Fig. 2.

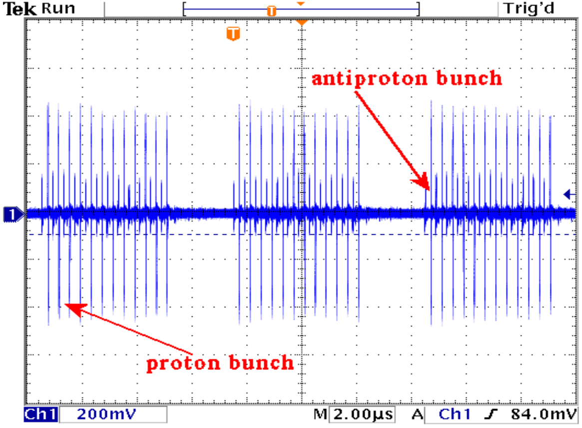

Figure 2: One turn beam signal.

With the bunch separation of 200 ns, the proton intensity 3-5 times higher than the antiproton one and the fact that the common mode suppression works for one beam at a time, acquiring the antiproton signal is challenging due to long persisting ringing induced by the proton bunches. In addition low frequency beam motion consumes the most of the available dynamic range and limits achievable sensitivity making additional beam excitation necessary. Fig. 3 shows the amplified single

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proton bunch A-B signal after careful delay and amplitude adjustment. Circled is the area most affected by the low frequency beam motion.

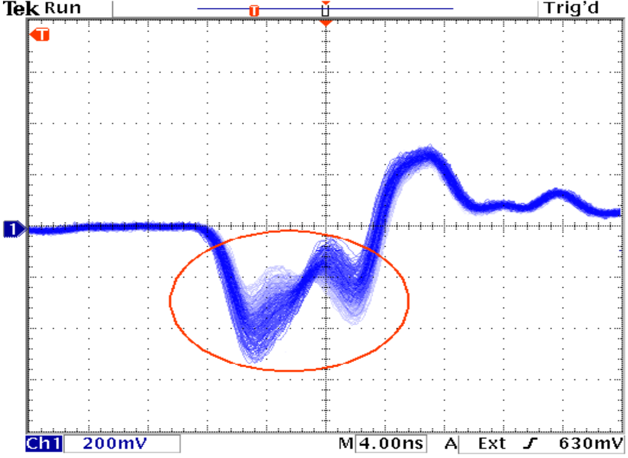

Figure 3: Amplified proton bunch A-B signal. Circled is the region affected by the low frequency beam motion.

Fig. 4 shows the single bunch waveforms recorded with a 10 bit digital oscilloscope, at a rate of 4 GS/s. The green curve represents the useful signal derived by subtracting the average (over all recorded turns) signal shown in blue from the single turn one. The dipole moment is plotted in red.

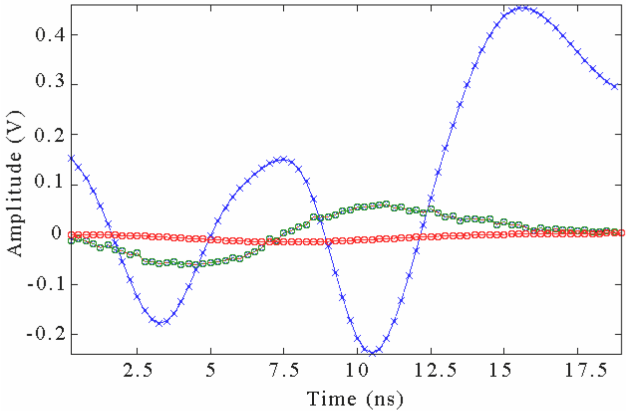

Figure 4: Proton bunch waveforms: average difference signal – blue, single turn signal with average subtracted – green, single turn dipole moment – red.

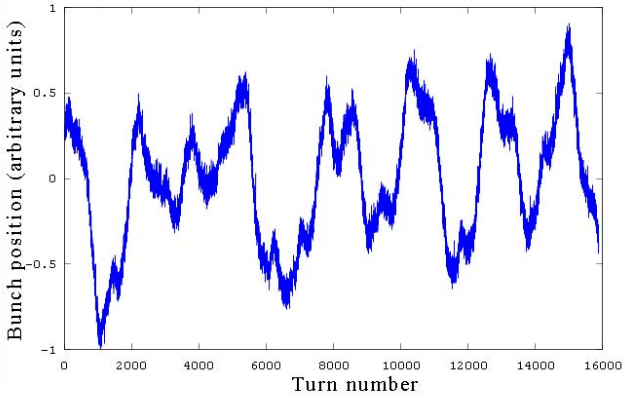

Figure 5: Proton bunch position over 16000 turns. Full vertical scale corresponds to ~25 µm.

Fig. 5 shows the 16000 turns of data in time domain. The same data is shown in Fig. 6 in frequency domain. Note that the signal is dominated by the low frequency beam motion. The strongest lines are the harmonics of 60 Hz mains power. The 15 Hz and the 0.45 Hz components can be explained by the effects of the fast cycling Booster synchrotron and the Main Injector on the power distribution systems at FNAL.

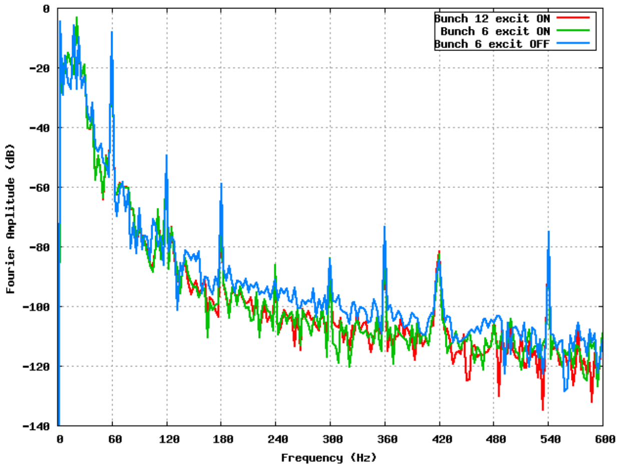

Figure 6: Spectrum of low frequency proton bunch motion.

MODELING OF BEAM-BEAM MODES

Transverse particle oscillations in the Tevatron are substantially nonlinear due to the properties of focusing and beam-beam force. Hence, the rigid bunch approximation can not provide an accurate view of the coherent mode spectrum. Still, this approximation can be used for qualitative analysis of the expected beam-beam mode tunes and their dependence on major machine parameters, such as the betatron tunes and the beam-beam parameter.

We used a simple matrix formalism to compute the eigen mode tunes of the system of colliding bunches in the Tevatron. Besides employing the rigid bunch model, one more simplification was implemented. The complete description of the system would require modeling of interaction of 72 bunches at 138 collision points. Both realization and analysis of such a system can be quite complex. Observations and analytical estimates show that the difference in tunes between individual bunches is small compared to the beam-beam tune shift. Thus, we believe it is feasible to exclude the long range interactions from consideration. This limits the system to 6 bunches (3 in each beam) colliding at two head-on IPs. Since the system has a three-fold symmetry, the one-turn map transporting the dipole moments and momenta of the bunches is expressed as

$$M = M_{bb3}M_{t3}M_{bb2}M_{t2}M_{bb1}M_{t1}$$

where M_{tN} are the 12x12 matrices transporting phase space coordinates through the arcs, and M_{bbN} are the matrices describing thin beam-beam kicks at the IPs. The eigen tunes of the map are then computed numerically. In Fig. 7 a sample dependence of the coherent mode tunes on the beam-beam parameter per IP ξ is presented. As one would expect, at small values of ξ the mode tunes approach bare lattice tunes for protons and antiprotons (0.583 and 0.574, respectively). At the values of x exceeding the difference between the lattice tunes the modes are split.

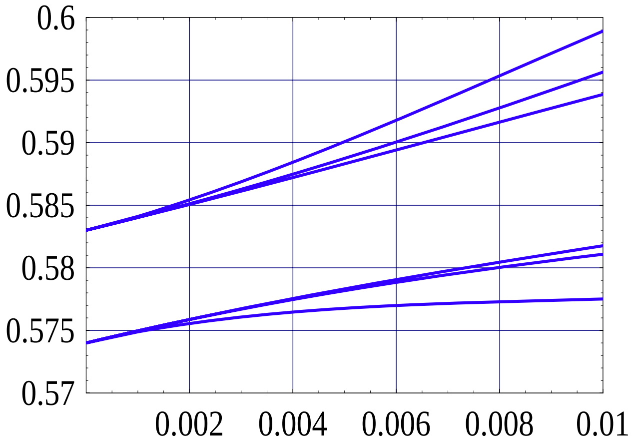

Figure 7: Coherent mode tunes vs. beam-beam parameter (calculation). Qp=0.583, Qa=0.574.

EXPERIMENTAL RESULTS

Fig. 8 shows the single bunch coherent spectra acquired during store #6200. At the time of measurement the beam-beam parameters for protons and antiprotons were approximately 0.008. Note that both spectra show peaks at the same tunes. Additional beam excitation was only applied to protons. One can assume that the peak in the antiproton spectrum at 0.58 corresponds to the lower lines in Fig. 7 and the lines at 0.585, 0.59 represent the upper cluster. The large amplitude peak at 0.565 can not be readily explained because of the lack of reliable measurement of the antiproton tune.

Figure 8: Single bunch proton and antiproton coherent mode spectra.

Fig. 9 presents the spectra of proton bunches #6 and #12 recorded in store #6200. As expected from analytical estimates the vertical tune of the last bunch in the train (#12) is lower than the average tune by 0.003. The higher amplitude of oscillation of bunch #12 may be explained by this bunch having lower chromaticity owing to long range beam-beam interactions.

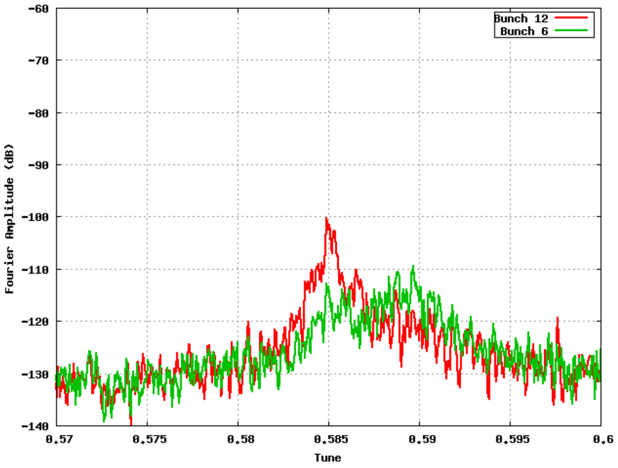

Figure 9: Comparison of spectra of proton bunches #6 and #12.

SUMMARY

Recent operation of the Tevatron collider in the strong-strong beam-beam regime caused a boost of interest to the experimental investigation of coherent beam-beam effects. A simple setup allowed turn-by-turn sampling of the transverse proton and antiproton bunch position with submicron resolution. The low frequency beam motion poses a limit on the achievable resolution. First results provide evidence of coherent beam-beam modes. The calculations performed using a simplified matrix model are in qualitative agreement with the observations. Further investigation is required to study the dependence of mode parameters on intensities, betatron tunes, etc.

ACKNOWLEDGEMENT

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