Bunch-by-bunch measurement of transverse coherent modes from digitized single-BPM signals in the Tevatron

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1. INTRODUCTION

A system was developed for bunch-by-bunch detection of trasverse proton and antiproton coherent oscillations based upon a vertical BPM signal digitized over a large number of turns. The main purposes of this project are tune diagnostics and the study of compensation of beam-beam effects with electron lenses.

In the Tevatron, 36 proton bunches collide with 36 antiproton bunches at the center of mass energy of 1.96 TeV. The bunches of each species are arranged in 3 trains of 12 bunches circulating at a revolution frequency of 47.7 kHz. The bunch spacing within a train is 396 ns corresponding to 21 53-MHz rf buckets. The bunch trains are separated by 2.6-μs abort gaps. The betatron tunes and tune spreads of individual bunches are affected, among other phenomena, by the head-on and long-range beam-beam interaction. These mechanisms limit the performance of modern colliders. In order to be able to mitigate the beam-beam effects, the knowledge of the bunch-by-bunch tune distribution is crucial.

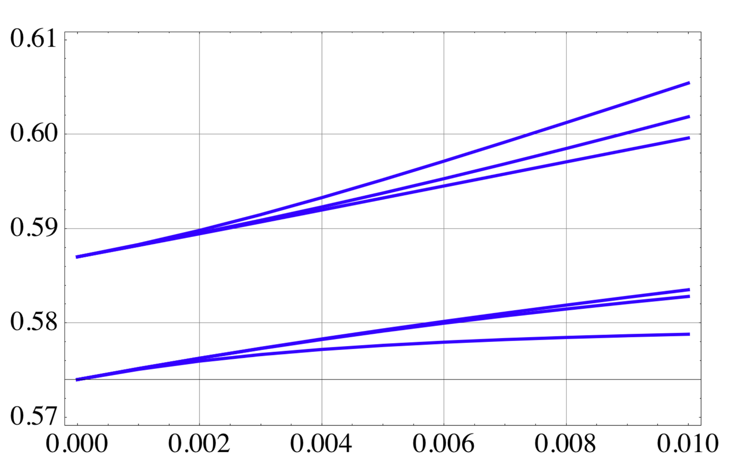

Figure 1: *Calculation of transverse coherent modes vs beam-beam parameter.*

Transverse coherent modes carry information about lattice tunes and the beam-beam parameter. In the simplest case, when 2 identical bunches collide in 1 interaction region, 2 modes appear: a σ-mode at the lattice tune, where the bunches oscillate in phase, and a π-mode separated by the beam-beam parameter, at which the bunches are out of phase. In general, the frequency and number of these modes depend on number of bunches and interaction regions, tune separation, beam sizes and relative intensities.

Figure 1 shows how the frequencies of the modes evolve as a function of the beam-beam parameter, in the case of 3×3 rigid bunches and 2 head-on crossings. This simplified model captures the essential features of collisions in the Tevatron.

2. APPARATUS AND DATA ANALYSIS

The system is based on the signal from a single vertical BPM, VB11, located in a region with large amplitude function (β_y = 900 m at collisions). It is a stripline detector, with A and B outputs for both protons and antiprotons.

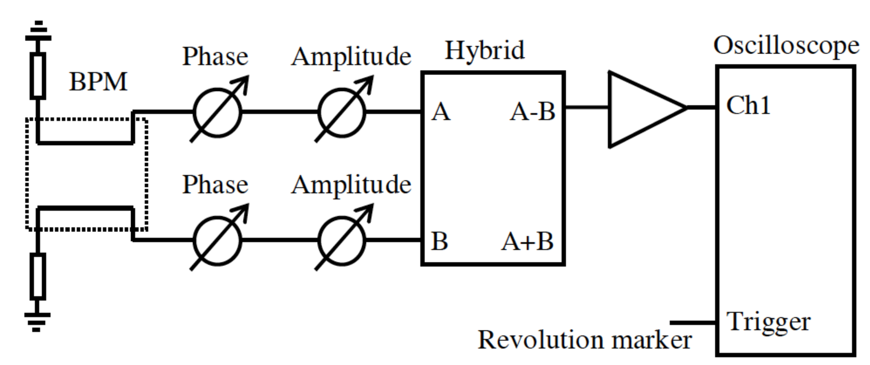

Figure 2: *Schematic diagram of the apparatus.*

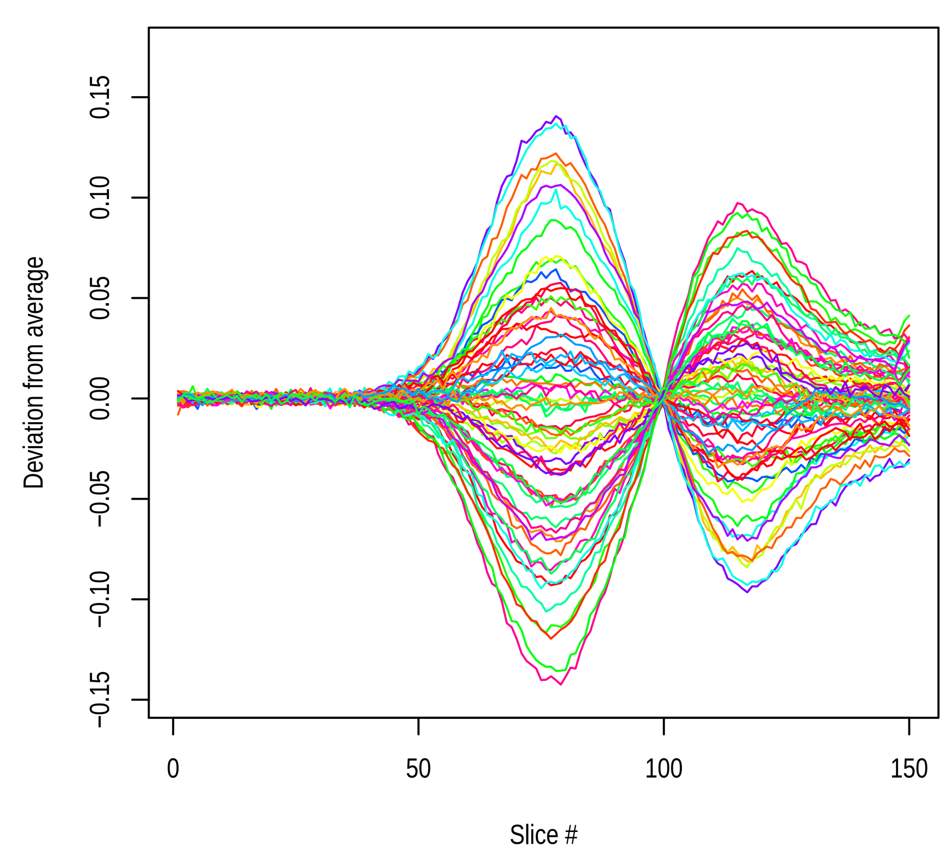

Figure 3: *Difference signal from the VB11 BPM in volts vs slice number.*

Before processing, it is necessary to equalize the A and B signals to take advantage of the full dynamic range of the digitizer without saturating it. Equalization also reduces false transverse signals due to trigger jitter. The phase and attenuation of each signal is manually adjusted before feeding it to the hybrid circuit by looking at the $A - B$ output. Fine adjustment can be achieved with a small orbit bump. The output is then amplified by 23 dB.

The difference signal is acquired using a 1-channel, 1-V full range, 10-bit digitizer with time-interleaved ADCs (Agilent Acqiris U1065A-DC22) that can sample at 8 GS/s and store a maximum of 1024 MS or 125,000 segments. The 47.7-kHz Tevatron revolution marker is used as trigger. When sampling at 8 GS/s, 150 samples or slices are reported for each 19-ns rf bucket. Each segment will include samples from all the bunches of interest.

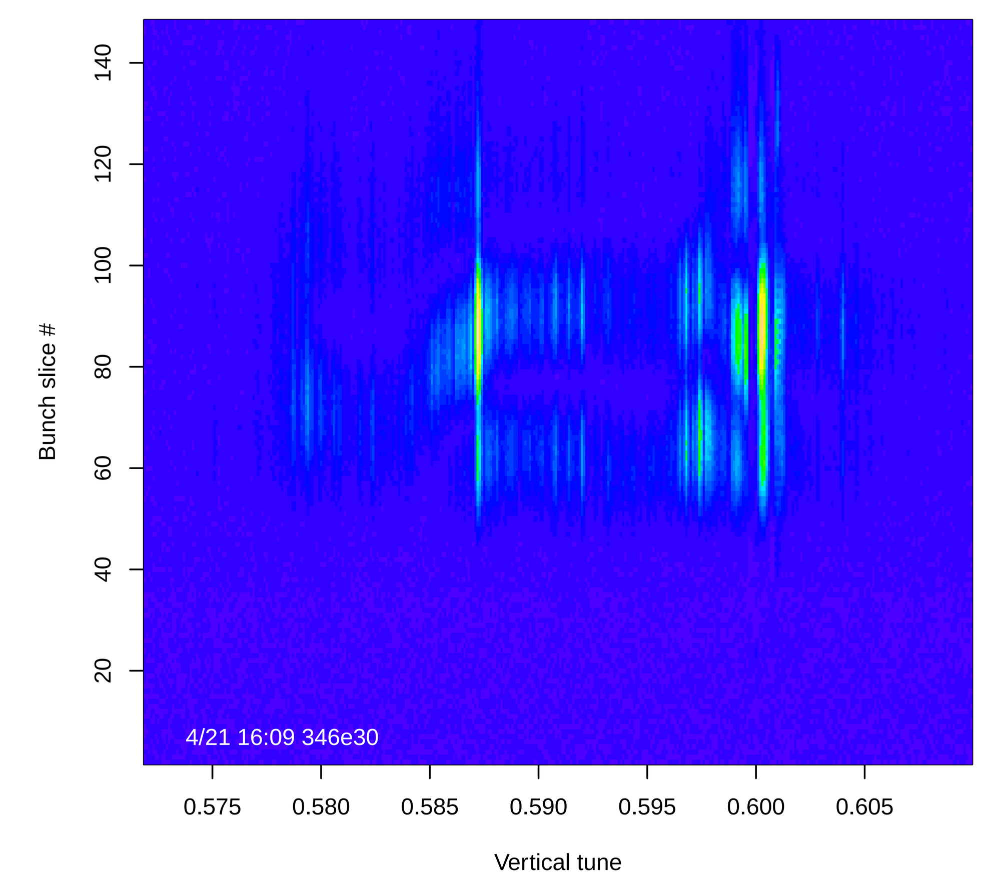

Figure 4: *Spectral power density for each bunch slice.*

To enhance the signal, the beam is excited with band-limited noise for a few seconds during the measurement. The typical measurement procedure includes digitizer setup, tickler turn-on, acquisition start, and tickler turn-off. The cycle takes a few seconds. The procedure is parasitical and it was shown not to affect the circulating beam even at high luminosity.

The trigger and sample time stamps are recorded together with the raw ADC data. Timing information is essential to synchronize samples from different turns. Without synchronization, jitter in the trigger signal translates into false transverse oscillations where the signal has a large slope. If the BPM signals are not well balanced, jitter of even a fraction of a nanosecond can raise the noise floor by several dB and compromise the measurement.

For each bunch, the signal of each slice vs turn number is Fourier transformed. The number of bins in the FFT vector is chosen according to the desired frequency resolution. The data is multiplied by a Slepian window to confine leakage to the adjacent bins. To reduce data loss from windowing, the FFT vectors are overlapped and averaged.

To improve the signal-to-noise ratio, and to suppress backgrounds that are unrelated to the beam, such as the spurious lines from the time-interleaved ADCs, a set of signal slices and one of background slices are defined. The power spectrum is given as the ratio between signal and background powers.

3. RESULTS

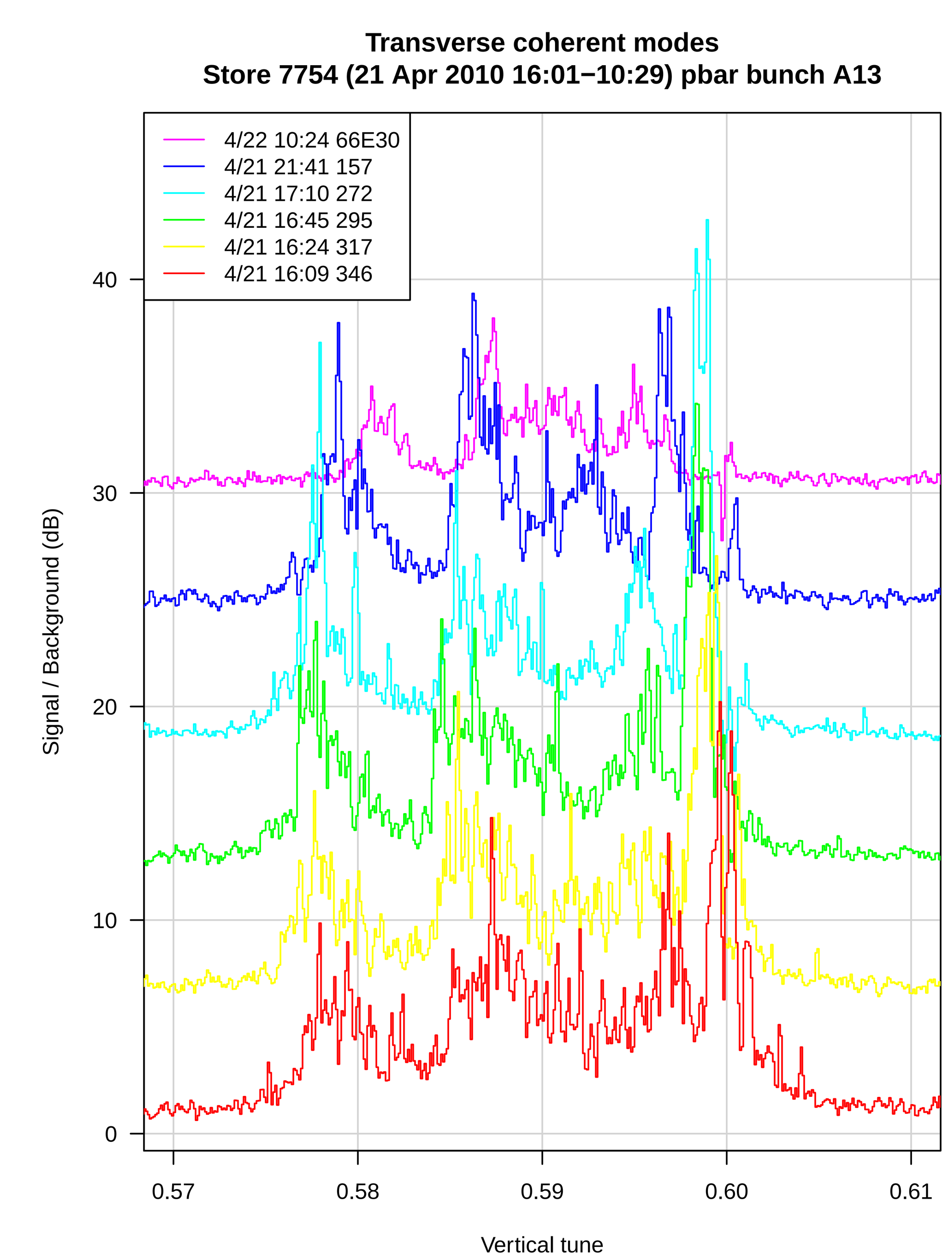

Figure 5: *Evolution of transverse coherent modes during a store (measurements offset for clarity).*

As an example of the performance of the system with antiprotons, Figure 5 shows the evolution of the transverse coherent modes in the vertical plane as a function of time in the store. The lattice tune was intentionally changed between the last 3 measurements to keep its average constant as the beam-beam forces decrease in strength.

One can observe a decrease in mode separation, in agreement with the decrease of beam-beam forces. The peaks corresponding to the synchrotron sidebands are also visible, both in the spectra and in the 2D FFT map. Notice also the low noise level.

4. CONCLUSIONS

We have successfully impemented a system to cleanly detect transverse coherent modes of single proton and antiproton bunches in the Tevatron. The device is being used for tune measurements. It is also one of the main diagnostic tools for the study of nonlinear beam-beam effects in the Tevatron collider and their compensation with Gaussian electron lenses.

5. ACKNOWLEDGEMENTS

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