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DIGITAL DOWN CONVERSION TECHNOLOGY FOR TEVATRON BEAM LINE TUNER AT FNAL

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Abstract

Fermilab is presently in Run II collider operations and is developing instrumentation to improve luminosity. Improving the orbit matching between accelerator components using a Beam Line Tuner (BLT) can improve the luminosity. Digital Down Conversion (DDC) has been proposed as a method for making more accurate beam position measurements. Fermilab has implemented a BLT system using a DDC technique to measure orbit oscillations during injections from the Main Injector to the Tevatron. The output of a fast ADC is down-converted and filtered in software. The system measures the x and y positions, the intensity, and the time of arrival for each proton or antiproton bunch, on a turn-by-turn basis, during the first 1024 turns immediately following injection. We present results showing position, intensity, and time of arrival for both injected and coasting beam. Initial results indicate a position resolution of ~20 to 40 microns and a phase resolution of ~25 ps.

Introduction

In order to preserve transverse emittance, it is important to match the ideal beam trajectory between synchrotron machines [1]. The Tevatron BLT is used to measure orbit oscillations during injections of protons and antiprotons from the Main Injector into the Tevatron. Digital Down Conversion (DDC) has been proposed as a method for making more accurate beam position measurements [2][3]. Fermilab has implemented a prototype BLT system using a DDC technique in software to measure orbit oscillations during injections.

The DDC BLT system measures the x and y positions, the intensity, and the time of arrival for each proton or antiproton bunch, on a turn-by-turn basis, during the first 1024 turns immediately following injection. Antiprotons are transferred into the Tevatron in 9 injections of 4 bunches each while protons are transferred in 36 single bunch injections.

The BLT System

The BLT consists of two pairs (horizontal and vertical) of bi-directional strip-line pickups installed in the Tevatron F0 interaction region. Each plate of a strip-line is 1.0 m long by 60∀wide, mounted at a distance of 41mm from the mechanical center of the beam pipe. Each strip-line has a measured sensitivity of 0.65 db/mm. As the beam passes through the BLT it induces capacitive signals on the plates. The difference between the signals on the plates is sensitive to the position of the beam. The time of arrival of the pulses is sensitive to longitudinal oscillations of the beam. Signal cables are connected to both ends of each pickup to measure the bi-directional beams. Protons induce signals on the downstream cables while antiprotons induce signals on the upstream end. The strip-lines have ~30-db directionality and the proton signal is much larger that the antiproton signal, so some of the proton signal is seem on the antiproton side of the strip-line. Since the proton and antiproton signals are separated in time by about 190 ns, the proton signal does not contaminate the antiproton signals.

Analog Processing

The plate signals are transported from the accelerator to the BLT electronics, amplified and digitized using a 100 MHz 12-bit Struck Model SIS3300 digitizer. The digitizer is clocked with a 106 MHz TTL level square wave synchronized to the 53 MHz Tevatron RF. The digitizers are triggered prior to the arrival of each bunch signal by an accelerator beam event signal. Thirty-two samples are collected for each bunch on each turn for the first 1024 turns.

The 19 ns doublets produced by bunches passing between the pickups are too fast to be directly digitized using a 100 MHz ADC. To adequately sample the waveform from the strip-lines, the pulse is stretched in time using a ringing filter. To avoid systematic effects, the ringing must damp before the next bunch arrives, and the impulse response of the filters on the A and B channels must also be well matched.

Digital Signal Processing

The sampled ringing waveform is frequency-shifted to base-band by multiplying by a complex exponential oscillating at the resonant frequency of the pulse-stretching filters. The base-band conversion effectively rectifies the pulse along some direction in the complex plane. The real part contains the rectified waveform while the imaginary part contains a rapidly oscillating waveform that will filter to zero. The complex envelope of the signal could be extracted by low-pass filtering the base-banded waveform.

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Instead of low-pass filtering, the base-banded waveform is matched-filtering, i.e. the waveform is correlated with a reference signal corresponding to the envelope of the expected signal. The peak amplitude of the output of the matched-filter provides the optimal linear estimate of the amplitude of a known signal in the presence of noise. The reference signal for the matched-filter is shown in Figure 1. The real and imaginary parts and the magnitude of the simulated signal following matched-filtering are shown in Figure 2.

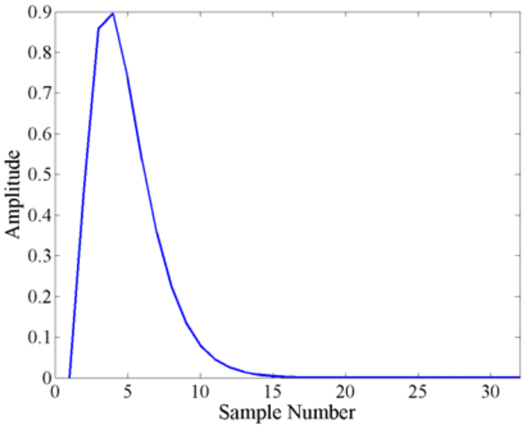

Figure 1. Matched-filter reference waveform.

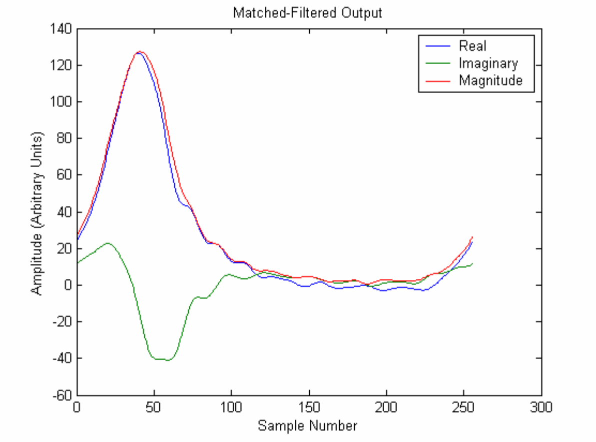

Figure 2. Output of the Matched-Filter.

The transverse position of the beam is estimated by taking the ratio of the difference between the peak amplitudes of the processed signals from the A and B plates divided by the sum of the peak amplitudes:

$$x \mid 26.7mm \Delta \frac{A_{Peak} \; 4 \; B_{Peak}}{A_{Peak} \; 2 \; B_{Peak}}$$

The conversion constant of 26.7 mm has been determined prior to the installation of the strip-lines by scanning a pulsed wire across the aperture.

The phase of the matched-filtered signal contains information about the time of arrival of the doublet relative to the trigger. With each successive pulse, the time of arrival of the pulse relative to the trigger is systematically delayed. As the time of arrival changes, the power in the signal moves from the real component into the imaginary component and back again. The phase of the peak of the filtered signal provides an estimate of the time of arrival of the doublet. Each of the four pickups in the BLT provides an independent measurement of the time of arrival of the bunch.

The relative time of arrival of the pulse measured by each pickup is estimated by dividing the phase of the peak amplitude by 2ϕ times the resonant frequency of the pulse stretching filters:

$$t \mid \frac{1}{2\phi f_{Filter}} \tan^{41} \left(\frac{\mathrm{Im}/ A_{Peak} \, 0}{\mathrm{Re}/ A_{Peak} \, 0} \right)$$

An overall time of arrival for each bunch is obtained by averaging the time of arrival measured by each of the four pickups.

Performance

Figure 3 and Figure 4 show the horizontal, vertical positions for the four antiproton bunches of as a function of turn at injection. Both the horizontal and vertical positions show rapid variations characteristic of betatron oscillations. The horizontal position also shows the slower variations associated with synchrotron oscillations.

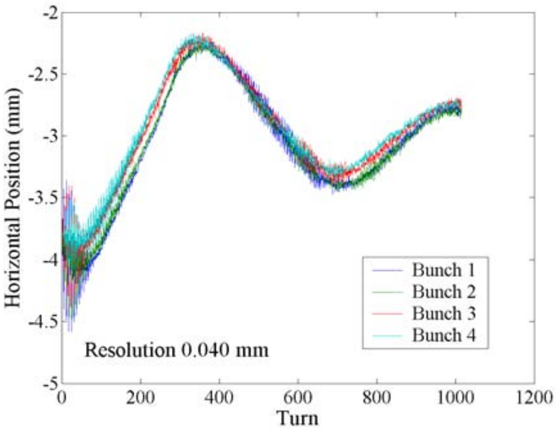

Figure 3. Horizontal positions following injection.

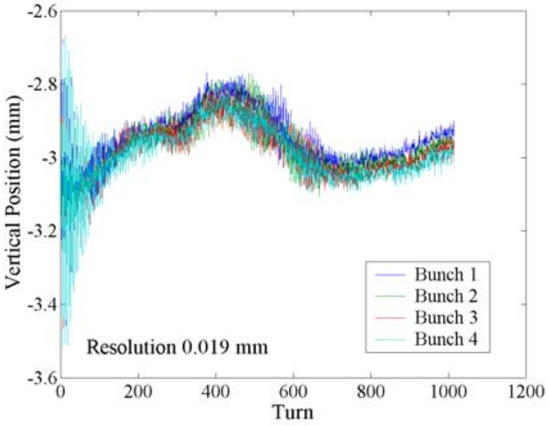

Figure 4. Vertical positions following injection.

Fourier transforms of the horizontal and vertical position measurements are shown in Figure 5 and Figure 6 respectively. Both distributions show clear peaks associated with the tunes of the Tevatron. The noise floor of the Fourier transform provides a model-independent estimate of the position resolution of the measurement. The horizontal and vertical resolutions estimated in this way are 0.040 mm and 0.019 mm respectively.

Figure 7 shows the time of arrival for each of the four antiproton bunches calculated from the phase of the processed signals. For each bunch, the time of arrival has been calculated by averaging the time determined by each the four plates (Horizontal A and B, and Vertical A and B). The noise floor of frequency spectrum of this time series corresponds to a resolution of ~25 ps.

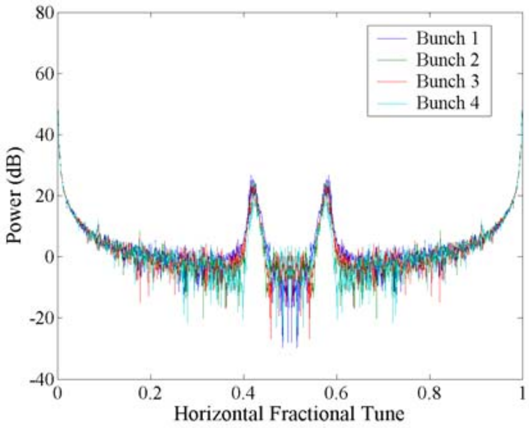

Figure 5. Horizontal tunes at injection.

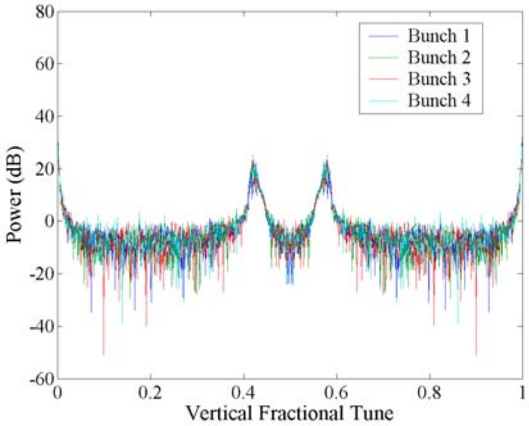

Figure 6. Vertical tunes at injection.

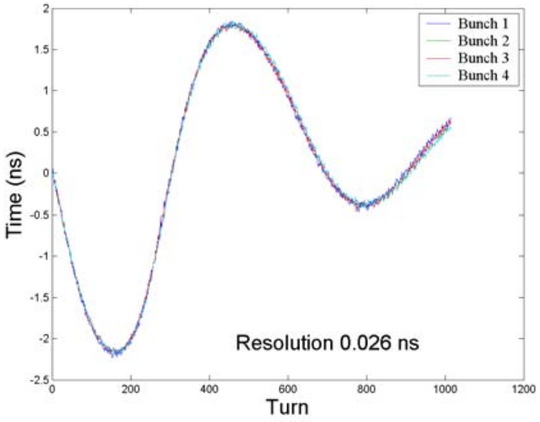

Figure 7. Relative time-of-arrival following injection.

Summary

We have used digital signal processing to measure the orbit oscillations during injections from the Main Injector to the Tevatron. The system measures the *x* and *y* positions, the intensity, and the time of arrival for each proton or antiproton bunch, on a turn-by-turn basis, during the first 1024 turns immediately following injection. We are able to measure the transverse position of the beam to a precision of ~20 to 40 microns per turn. We are able to measure the time of arrival of the bunch to a precision of ~25 ps per turn.

Acknowledgements

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References

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