FIRST RESULTS OF A LONGITUDINAL PHASE MONITOR AT THE TEVATRON

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Abstract

A digital beam phase monitor has been installed on the TEVATRON ring. This device will be mainly use to diagnose the energy oscillations of each of the 36×36 proton and antiproton bunches as well as to study the transient beam loading. The first results obtained from the beam phase monitor is presented on the paper.

INTRODUCTION

The Fermilab TEVATRON is colliding 36 proton against 36 antiproton bunches with an energy of 1.96 TeV at the center of mass. The bunches are equally separated in 3 trains. The bunch spacing within a train is ~396 ns corresponding to 21 RF buckets (53.106 MHz) and 139 empty buckets (~2.6 μs) separate the trains. A longitudinal phase monitor has been developed in order to measure the phase of each proton and antiproton bunch with respect to the RF. This paper presents the first results obtained with the longitudinal phase monitor which is operational at the TEVATRON since January 2005. Our experimental results are limited to one single coalesced proton bunch (the behavior with uncoalesced bunches as well as antiproton bunches being under investigation).

SYSTEM OVERVIEW

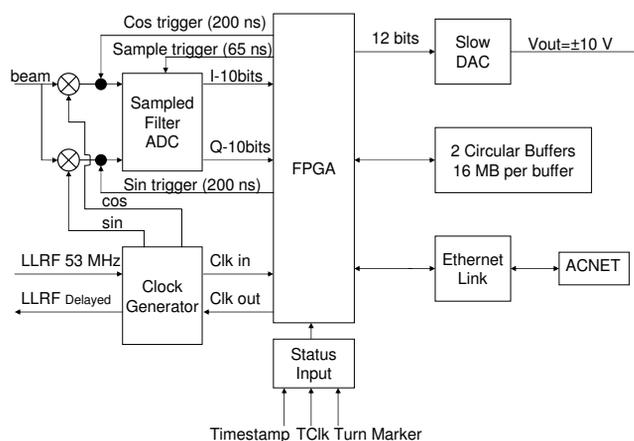A schematic layout of the longitudinal phase monitor is presented in Figure 1.

Figure 1: Schematic of the longitudinal phase monitor.

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Inputs

The input signal is supplied by summing the signals as the beam passes a top and bottom vertical strip lines located at the E0 hall. The strip lines signal is first received by a differential amplifier (not reported in Figure 1) which provides balanced output gain and phase matching. From the differential output, the signal is multiplied by a sine and cosine waveforms created by a lookup table with both phases locked to the 53 MHz input reference frequency. The sine and cosine products are each integrated in parallel over a 200 ns gate. The two integrated sine ("I") and cosine ("Q") products are then sampled by a 20 Msps, 10-bit Analog Digital Converter (ADC). The ADC clock has a period of ~65 ns. On the rising clock edge, the ADC samples both input channels. Valid data "I" and "Q" are available 3 clock cycles later. A Field Programmable Gate Array (FPGA) controls the synchronization so that the ADC samples at the end of the integration gate. The FPGA performs also the phase calculation by dividing "Q" samples by "I" samples and taking the arctan of the result. The final phase calculation is a 12-bit result.

Outputs

The longitudinal phase monitor provides three output modes : SLOW Digital Analog Converter (DAC), Circular Buffers and Oscillation Amplitude Detector. In the present time, only the two first are operational.

In the SLOW DAC mode, each phase of the selected bunch is calculated every turn and averaged over 128 turns. The resulting average phase is then converted into a voltage, using a 12-bit serial input DAC. This gives an effective output rate of 373 Hz.

The longitudinal phase monitor includes an external memory blank, consisting of two 10 minutes LIFO circular buffers. The format of the buffers consist of sequential arrays of 39 elements each. Each array, completed every 128 turns, has the following format:

1. an incrementing 32-bit sample count, indicating the start of the buffer

2. a 16-bit average phase of the following 36 data elements

3. the 16-bit average phase over 128 turns for each of the 36 bunches

Each buffer has the capability to be started and stopped either by a manual trigger or by a programmed TCLK

event. These controls can be accessed via the ethernet or the ACNET controls system.

In the Oscillation Amplitude Detector mode, the same 39 element array will be processed to output an envelope that contains the magnitude of the phase variation for each bunch. This output is still in progress.

EXPERIMENTAL RESULTS

Synchronous Phase on the Ramp

Figure 3 shows the phase of the first proton bunch (LPM001) given by the longitudinal phase monitor during the ramp of store ♯4121, the 30th of April 2005. As reported in this figure, the energy (ERING) rises from 150 GeV to 980 GeV in ~80 sec, the longitudinal emittance (SBDPLS) stays at a value of $\epsilon_z \simeq 3.5$ eV-sec before and after the ramp while the bunch length (SBDPWS) decreases from ~2.84 ns to ~1.7 ns. The initial peak luminosity for this store was in the order of $1.2e32$ cm^{-2}s^{-1}.
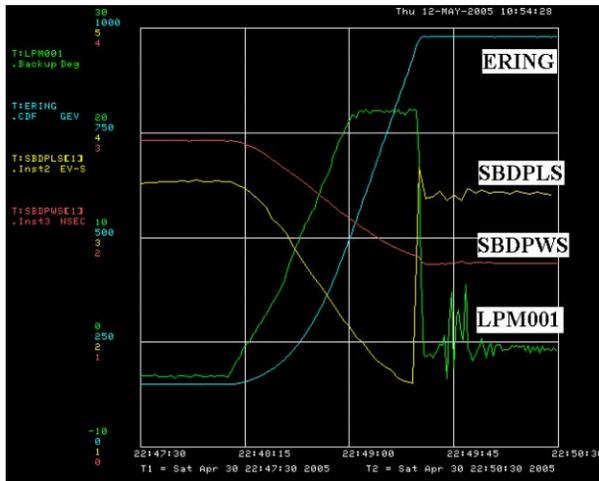

Figure 2: Phase of the first proton bunch (LPM001) from the longitudinal phase monitor, energy (ERING), longitudinal emittance (SBDPLS), and bunch length (SBDPWS). Datas are taken during the ramp of store ♯4121.

The 1 Hz outputs of the longitudinal phase monitor of Figure 2 were exported and compared to an analytical model and to the simulation code ESME [1]. These comparisons are shown in Figure 3. The phase of the analytical model is reported using equation (from [2]):

$$\phi_s = \arcsin\left(\frac{2\pi R^2 \dot{B}}{V_{rf}}\right) \tag{1}$$

that describes the phase of the synchronous particle in a synchrotron of radius R, $\dot{B}$ and V_{rf} being respectively the derivative of the magnetic field and the peak accelerating voltage. In our model, $R = 10^3$ m (Tevatron's radius), $\dot{B}$ was extracted from the energy reported in Figure 3 (using the definition of the magnetic rigidity, see [3] for example)
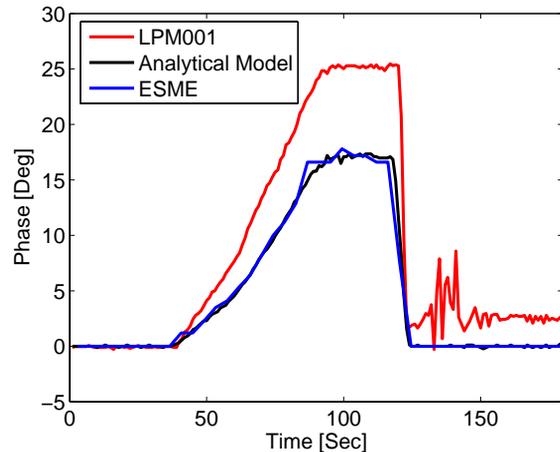

Figure 3: Comparison between the longitudinal phase monitor (LPM001), an analytical model and ESME during the ramp of store ♯4121.

and $V_{rf} = 1.16$ MV (as indicated by the control system). ESME is a code developed to model the beam behavior in a synchrotron. The energy during the ramp was imported into ESME using an external file.

As indicated in Figure 3, the phase of the longitudinal phase monitor was set to zero degree at injection (150 GeV) in order to have the same reference than the analytical model and ESME. Just after flat-top (980 GeV), the longitudinal phase monitor showed some instabilities that has been reported in [4] to be due to the cogging process (which consists in changing the frequency of the antiproton accelerating cavities relative to the proton cavities to properly space the proton and antiproton so they collide at the correct place around the ring). We think this is also the reason for which the phase of the longitudinal phase monitor does not come back to a zero value once at flat-top.

Figure 3 indicates that the phase reported by the longitudinal phase monitor during the ramp is ~48% higher that the phase of the analytical model or ESME. We believe that two reasons are responsible for this difference: the first reason ([5]) is that the longitudinal phase monitor responds to the centroid of the bunch while the analytical model and ESME report the synchronous phase of the bunch. In the case of an asymmetric bunch, the synchronous phase representing the peak of the longitudinal distribution is displaced with respect to the phase representing the centroid of the bunch. It has been observed [6] that during the ramp the bunch gets slightly asymmetric, the centroid of the bunch being displaced by ~0.2 ns (see Figure 4) with respect to the peak of the bunch, which corresponds to a difference of ~4 degrees. We think this is one reason for the disagreement observed in Figure 3. The second reason susceptible to explain the phase difference concerns the accelerating voltage. In fact, a value of V_{rf} in the order of 0.95 MV increases the phase by ~4 degrees (according to Equation
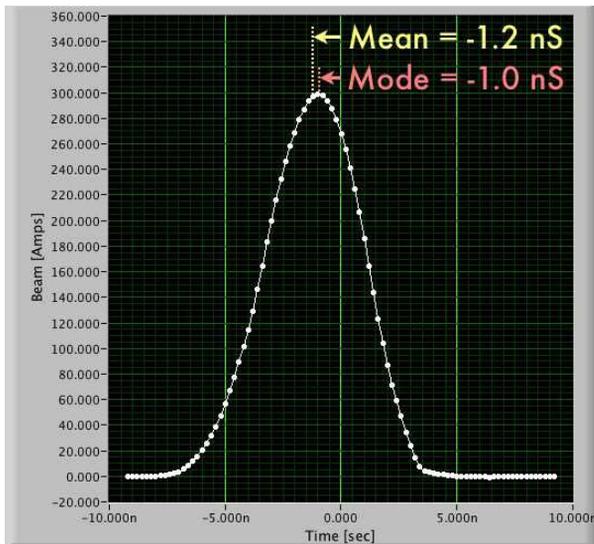
Figure 4: Longitudinal distribution of the beam during the ramp (610 GeV, store ♯ 4098). Courtesy of B. Flora.

1). An attempt to calibrate the accelerating voltage was done from the synchrotron frequency f_s using the equation (from [2]):

$$f_s = f_0 \times \sqrt{\frac{V_{rf} h \alpha}{2\pi E s}} \qquad (2)$$

that describes the frequency of the synchrotron oscillations of small amplitude, with f_0 being the beam revolution frequency, h the harmonic number, α the momentum compaction and E_s the beam energy. For the Tevatron, $f_0 \simeq 47.7$ kHz, $h = 1113$ and $\alpha = 2.821 \cdot 10^{-3}$ (from [7]). Reference [8] reports a synchrotron frequency at injection of $\sim$86 Hz (measured using a resistive wall monitor and a digital oscilloscope), which leads, using Equation 2, to a value of the accelerating voltage $V_{rf} \simeq 0.95$ MV. Even though this accelerating voltage has been calculated using the small amplitude oscillation approximation, its value is significantly lower than the one reported from the RF system (V_{rf}=1.16 MV) and may indicate that the accelerating voltage is overestimated by the RF system and therefore the phase reported by the analytical model and ESME in Figure 3 is underestimated. At this point, no further investigation on the accelerating voltage was undertaken.

Longitudinal Instabilities

Figure 5 displays instabilities ($\pm$1.5 degrees) of the first proton bunch detected by the longitudinal phase monitor during the store ♯4121, $\sim$1.5 hours after the ramp. These instabilities are also reflected by the bunch centroid (SBD-PCS) and create a slight increase of the bunch length (SBD-PWS). It is interesting to notice that few minutes after decreasing the gain of the longitudinal dampers (LDM1GV, [9]) from -3.5 V to -3.0 V, the longitudinal instabilities are
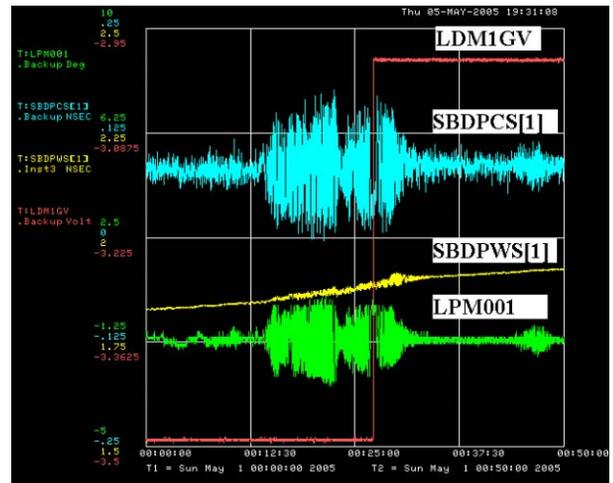

Figure 5: Longitudinal instabilities of the first proton bunch reported by the longitudinal phase monitor (store ♯ 4121).

damped. The reasons for these instabilities are under investigation.

CONCLUSION

A longitudinal phase monitor is successfully operational at the TEVATRON and has been setup to measure the phase of one proton bunch with an accuracy of 0.5 degree. It is intended that the phase of all the proton bunches will be monitored when the circular buffer will be available. A second phase monitor is foreseen to be installed for antiprotons.

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