TOWARDS ROUTINE OPERATION OF THE DIGITAL TUNE MONITOR IN THE TEVATRON *

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Abstract

Monitoring the betatron tunes of individual proton and antiproton bunches is crucial to understanding and mitigating the beam-beam effects in the Tevatron collider. To obtain a snapshot of the evolving bunch-by-bunch tune distribution a simultaneous treatment of all the bunches is needed. The Digital Tune Monitor (DTM) was designed to fulfill these requirements. It uses the standard BPM plates as a pickup. Operating the vertical proton monitor during numerous HEP stores allowed us to gain valuable experience. A major upgrade is underway to implement an automatic bunch-by-bunch gain and offset adjustment to maintain the highest possible sensitivity under real operational conditions. We present the concept of the DTM along with its technical realization as well as the latest experimental results. Major challenges from the design and operation point of view are discussed.

INTRODUCTION

In the TEVATRON 36 proton bunches collide with 36 anti-proton 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 around the ring with the revolution frequency $f_{rev} = 47.7$ kHz. The bunch spacing within a train is 396 ns corresponding to 21 RF buckets (53.1 MHz). The bunch trains are separated by 2.6 μs abort gaps corresponding to 139 RF buckets. The betatron tunes of individual bunches are affected, among other phenomena, by the head on and long range beam-beam interaction limiting the collider performance [1]. In order to be able to mitigate the beam-beam effects, the knowledge of the bunch-by-bunch tune distribution is crucial. Three transverse tune monitors are presently available at the Tevatron: the 21.4 MHz Schottky, the 1.7 GHz Schottky and the Direct Diode Detection Base Band Tune (3D-BBQ) detector [2]. The 21.4 MHz Schottky is used to measure the horizontal and vertical tunes of the 36 proton bunches (antiproton signal is attenuated by 20 dB) without the possibility of gating on individual bunches. The 1.7 GHz Schottky is capable of measuring the horizontal and vertical tunes of a single proton and anti-proton bunch but needs a few minutes of averaging time to get the precision of 10^{-4}. Furthermore, the significant width of the betatron sidebands at high frequency and the presence of transverse coupling in the machine result in additional uncertainty of the reported tunes. The 3D-BBQ detector is under development. This monitor showed promising results, but is not yet setup for measuring the tunes of individual bunches. The development of the DTM began with a proof of principle measurement using a RF hybrid and a fast digital oscilloscope followed by data analysis performed offline [3]. Today, the DTM, whose analog electronics also takes advantage of the 3D approach, utilizes digital techniques that make it possible to measure the bunch-by-bunch spectra without the necessity of using fast RF switches for gating [4]. The DTM has the potential to report the horizontal and vertical tunes of each proton and anti-proton bunch, at a repetition rate of 1 Hz.

RESULTS AND EXPERIENCE

The DTM was successfully used to acquire proton vertical spectra in numerous HEP stores [4]. Fig. 1 shows a vertical spectrum of the first proton bunch.

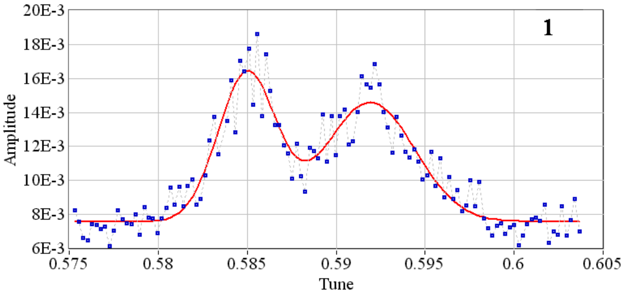

Figure 1: The vertical spectrum of the proton bunch #1. Points represent the average of 25 FFTs and solid line - the double Gaussian fit. The left peak corresponds to the vertical tune of 0.585, the right peak to the horizontal tune of 0.592.

The presence of transverse coupling in the machine accounts for the double peak structure of the spectrum. The data was taken during a HEP store using additional beam excitation (band limited noise). Since the excitation power is very low (a few watts) and is needed for about 2 s it makes no impact on the Tevatron operation.

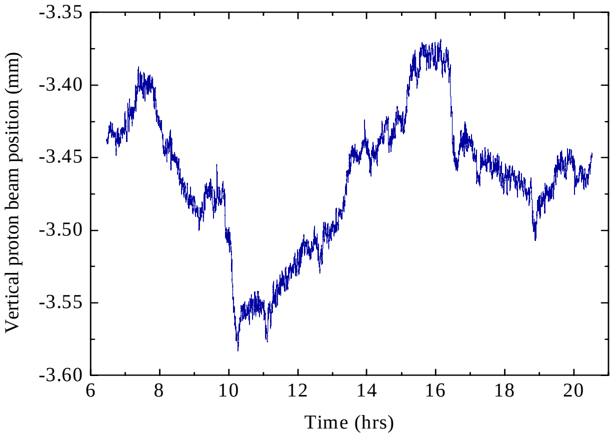

Figure 2: Vertical proton beam position reported by the Tevatron BPM over the course of a store.

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Estimates show, that detecting the betatron oscillation of individual bunches without additional beam excitation might be possible. However, under real operating conditions the ultimate achievable sensitivity and the dynamic range are limited by the orbit drifts (Fig. 2), low frequency beam motion (Fig. 3) and the bunch to bunch intensity and position variation (Fig. 4).

The present DTM design makes use of a linear discriminator in a feedback loop in the difference channel. This technique allows for compensation of the slow beam motion (based on the average position measured over several turns).

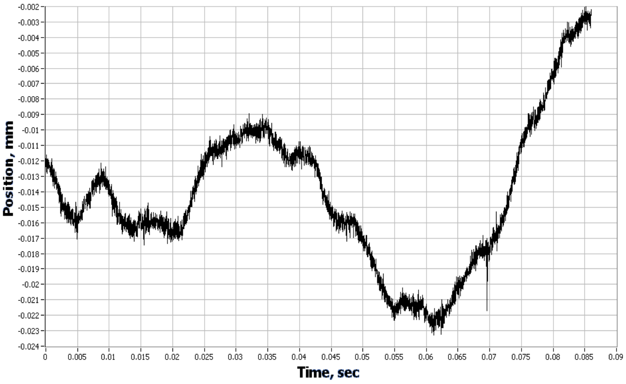

Figure 3: An example of the vertical proton beam position measured with the DTM. Full scale is 22 µm, 4096 turns.

The application of this method led to reproducible results but additional beam excitation is still necessary. The RMS position resolution of the DTM in the FFT averaging mode was estimated to be of the order of 100 nm. The frequency resolution is better than 12 Hz and can easily be improved by increasing the number of turns recorded. In the current configuration, 2.2 s are required to record 25 sets of 4096 turns. The averaged spectra for all 36 bunches are available in about 80 s.

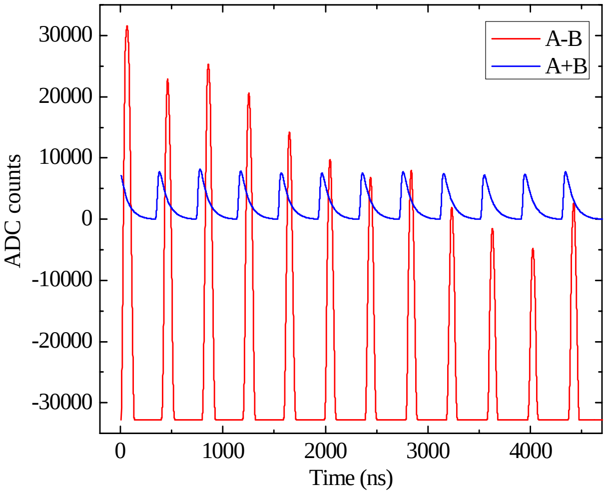

Figure 4: The integrated sum and difference signals in time domain recorded by the DTM. Proton bunches 1-12 are shown.

An adjustable attenuator was used for rough tuning compensating the beam position offset at the pickup location. The fine adjustment was done by changing the ADC offset.

As mentioned above the bunch to bunch variation in intensity and position significantly limits the dynamic range and the achievable sensitivity. Fig. 4 shows a snapshot (content of the ADC FIFO) of the A-B and A+B signals. The data represents a single passage of the beam through the pickup. The vertical scale corresponds to 16 bit – the full ADC range. The gain in the A+B channel is much lower than in the A-B channel. One can see that in this particular case the bunch to bunch amplitude variation, caused by the long range beam-beam effects and the different bunch intensities, consumes more than half of the available ADC range in the A-B channel. In extreme cases it can be the full range. Furthermore, beam motion can cause temporary saturation for some bunches leading to elevated noise floor in the spectra or even to data loss.

The phenomena described above pose a limit on the sensitivity of the DTM making the additional beam excitation necessary. To provide adequate beam excitation the DTM now includes a subsystem consisting of a two channel digital signal generator and two power amplifiers (PA). Since the betatron sideband of interest corresponds to 19.6 kHz, inexpensive commercially available audio PAs are used. The DTM does not have dedicated pickups and kickers; instead they are shared with existing systems by means of coaxial relays. Fig. 5 shows how the kicker and the pickup are shared with other Tevatron systems.

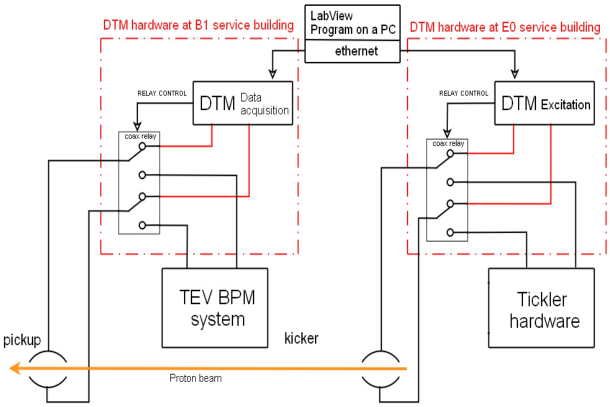

Figure 5: Block diagram of the DTM system.

THE NEW DEVELOPMENT

In order to cope with the issues described in the previous section the DTM is undergoing a major upgrade. Based on the operational experience we acquired, several additional techniques are being currently implemented. Fig. 6 shows the block diagram of the latest design. To effectively suppress the beam position offset at the pickup location in automatic manner the signals from individual plates are now integrated, amplified and digitized separately. The fast linear discriminator (LD) allows for efficient usage of the ADC dynamic range. Both the LD and the variable gain amplifier (VGA) are controlled by the FPGA via two fast DACs. The bunch-by-bunch

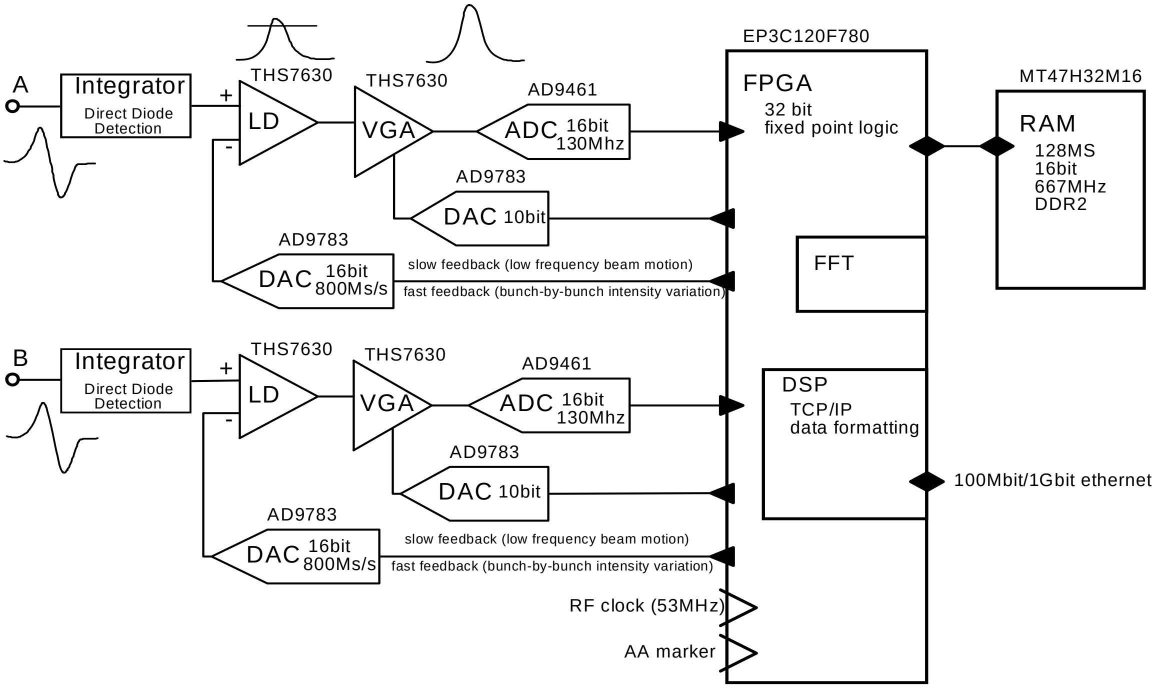

Figure 6: The block diagram of the new DTM design.

adjustment of the LD and the VGA compensate the bunch to bunch intensity and position variation as well as the slow beam motion. All the signal processing, including four parallel FFT engines and a DSP is realized in the large CYCLONE III FPGA. The DSP takes care of the data formatting and communication via 100/1000Mbit Ethernet link. The LD threshold is calculated using the orbit data (all bunches over several revolution periods) and the data describing the properties of each individual bunch. Before each tune measurement, the DTM goes through a “learning period” (several turns) when the data tables describing the individual bunches are derived. During the actual data taking these tables are used to adjust the LD and the VGA for predictable bunch parameters such as intensity and the position deviation of individual bunches with respect to the average beam position. Additional adjustment can be made “on the fly” as the beam motion frequencies are sufficiently low.

SUMMARY

The Digital Tune Monitor was successfully used in numerous HEP stores to acquire vertical spectra of all 36 individual proton bunches. However, the sensitivity limitations posed by the beam motion and bunch to bunch position and intensity variation make the use of additional beam excitation necessary. The DTM system now includes the beam excitation module – a digital noise source and an audio power amplifier. Occasionally, manual attenuator adjustment was necessary after orbit changes were introduced. Based on the operational experience, several additional features are now being added to the DTM design. The new hardware has been assembled; the FPGA code development is underway. The new design will allow compensating for the detrimental affects of the orbit changes and bunch to bunch intensity and position variation. These measures are expected to result in significant improvement of sensitivity and reliability of the DTM. In addition, parallel FFT processing in the FPGA will significantly reduce the system latency making the true real time bunch-by-bunch tune measurements possible.

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