STATUS OF THE FNAL DIGITAL TUNE MONITOR *

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Abstract

We have implemented a real-time method for bunch-by-bunch betatron tune measurements in the TEVATRON based on 16 bit 100 MHz ADC. To increase the betatron signal level from a pick-up we have used a modified version of Direct Diode Detector method combined with fast FPGA algorithm and a feedback loop utilizing a 14 bit DAC for suppression of low frequency beam motion. A description of this device is presented in this paper together with first results.

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 divided in 3 trains of 12 bunches. The bunch spacing within a train is ∼396 ns corresponding to 21 RF buckets (53.106 MHz) and each train is separated by ∼2.6 μs (abort gap) corresponding to 139 RF buckets. During the revolutions around the ring ($f_r \simeq 48$ kHz) the beam interacts with its environment which modifies the transverse tune of the trains and of the individual bunches.

Three transverse tune monitors [1] are presently available at the TEVATRON : a 21.4 MHz Schottky, a 1.7 GHz Schottky and a 3D-BBQ detector (Direct Diode Detector Base Band Q). The 21.4 MHz Schottky is used to measure the horizontal and vertical tunes of the 36 proton bunches 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 long averaging time (few minutes) to get a precision of $\sim 10^{-4}$. The 3D-BBQ detector is under development and allows to gate on proton and anti-proton bunches. This monitor showed promising results (individual proton and anti-proton tunes have been observed without the need of an external excitation) and is presently used to cross-check the tunes measured by the two other monitors.

The Digital Tune Monitor (DTM) under development at Fermilab has the potential to give the horizontal and vertical tunes of each proton and anti-proton bunch, at a 1 Hz repetition rate and with a high precision ($\sim 10^{-4}$). An external excitation of the beam is however necessary. A proof-of-principle for this new method of monitoring the tunes has been presented in Reference [2] using an oscilloscope to successfully measure the vertical tune of a single proton bunch in the TEVATRON at injection (150 GeV) and flat-top (980 GeV) energies. The current version of the DTM uses 16 bits 100 MHz ADC's which allows measuring the tunes on a bunch-by-bunch basis.

SYSTEM DESCRIPTION

The Digital Tune Monitor relies on a simple idea: sampling of the position of individual bunches for N turns ($N \sim 10^5$) and inspecting the power spectrum of the stored data computed by an FFT. A schematic of the DTM is presented in Figure 1 :

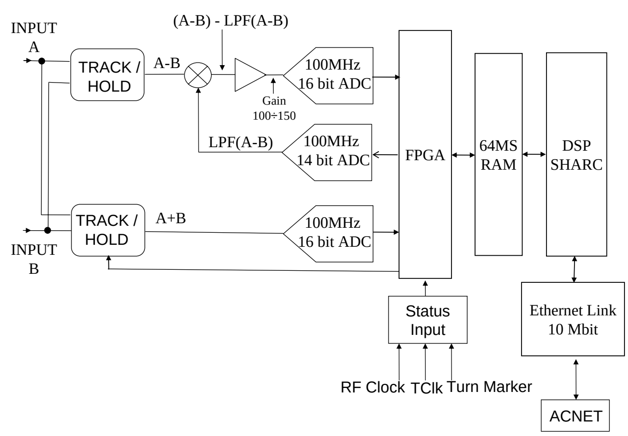

Figure 1: Schematic of the Digital Tune Monitor.

A displaced beam produces non-equal current distribution when passing by stripline electrodes. The signals from both electrodes are stretched using the Direct Diode Detection technique ([3]) and then added (A+B) and substracted (A-B), as presented in Figure 1. The low frequency beam motion is then substracted from the (A-B) difference using signals from the Low Pass Filter implemented inside the Field-Programmable Gate Array (FPGA). This corrected signal (referenced (A-B)-LPF(A-B) in Figure 1) is amplified by ∼100 before being digitized by a 16 bit, 100 MHz Analogue Digital Converter (ADC). The same digitization

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is performed on the (A+B) signal. The FPGA not only performs the low frequency correction but also synchronizes the data acquisition with the time domain beam structure using two external TEVATRON RF signals (the 53.106 MHz RF clock and the AA marker) and finally sends the datas to an SD-RAM. The SD-RAM has a maximum storage capacity corresponding to $\sim 10^5$ turns. The Digital Signal Processor (DSP) calculates the transverse displacement of the beam centroid for each bunches and performs a transformation of this signal into the frequency domain using a Float Point 32 bit FFT. It is important to notice that this calculation is performed by steps of $4 \cdot 10^3$ turns which implies that a maximum of ~ 25 power spectra are summed up. The determination of the transverse tune of each bunch is then performed by a Gaussian fit of the power spectrum.

EXPERIMENTAL RESULTS

Figure 2 shows the vertical tunes of the 36 protons bunches measured at the end of the store #5301 (March 2007) using the DTM. A vertical BPM at B1 was used as a pickup because of the large vertical beta function ($\sim$900 m) at this location. The length of the BPM striplines is $\sim$ 18 cm. The proton beam was excited by a vertical tickler (VTICK, located at the E0 hall) which consists of a bandwidth limited (5 kHz BW centered at a higher harmonic of the TEVATRON frequency) noise source and a power amplifier operating at about 5 Watts of output power. The vertical tunes presented in Figure 2 were obtained within 2 seconds. It has been proven that powering VTICK for such a short period does not impact the luminosity.

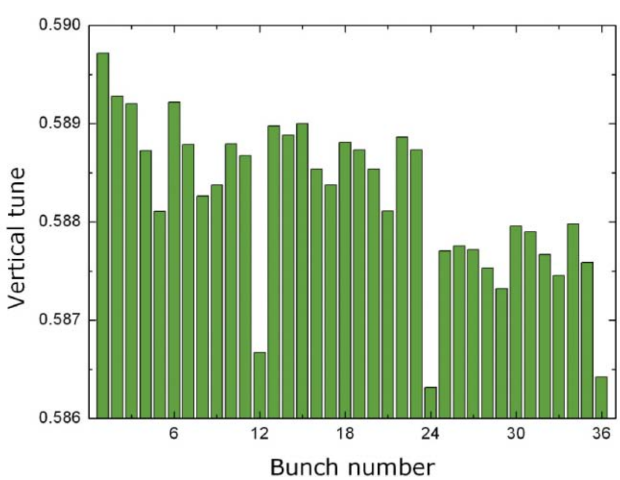

Figure 2: Vertical tunes of the 36 proton bunches measured by the DTM at the end of the store # 5301.

It is interesting to notice in Figure 2 that the last bunch of each train (#12, #24 and #36) has a lower vertical tune than the other bunches. Also the first bunches (#1, #13 and #25) present a high vertical tune. The tune spread in each bunch of the TEVATRON is mainly due to head-on collisions, but there is also a bunch-to-bunch tune spread due to

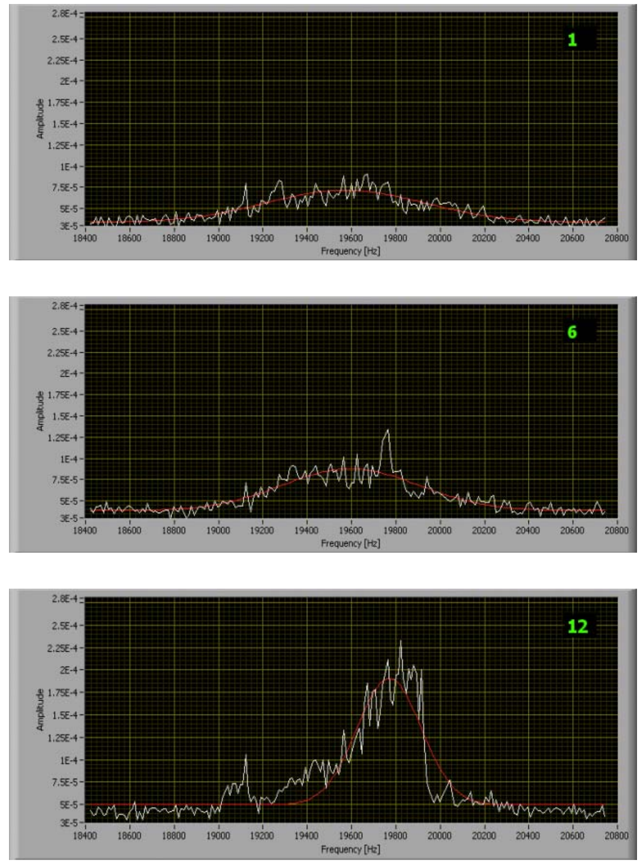

Figure 3: Spectra reported by the DTM for the first, the sixth and the twelfth bunch. Datas taken at the end of store #5301.

parasitic long-range beam-beam interaction [4]. Each proton bunch collides twice with an anti-proton bunch at the head-on collision points. For the long-range interactions, this is no longer the case. In fact, as previously discussed, the bunches in the TEVATRON do not form a continuous train of equidistant (equally spaced) bunches but an abort gaps of $\sim$2.6 μs between the three trains of 12 bunches are necessary to allow for the rise time of the kickers. The long range interaction pattern is different for the first and last bunches in each train as compared to other bunches. Proton bunches at the beginning and at the end of each train will encounter parasitic long-range beam-beam interactions only in one side of each interaction point and as a result experience fewer long-range beam-beam interactions than those in the middle. Therefore, as shown in Figure 2, those PACMAN bunches [5] have a different tune.

Figure 3 shows the corresponding spectrum and Gaussian fit for the first, the sixth and the twelfth bunch. A first observation from this figure concerns the overall shape of these spectra. We are aware of the fact that the spectra are not necessarily Gaussian (as presented for bunch #12 in Figure 3). We are currently working on more realistic fitting algorithm that would give more accurate values of the betatron tunes. Another observation from Figure 3 concerns the intensity of the last bunch of the train : it has been observed in the spectrum from the DTM that the last bunch of each train presents a stronger signal than the other bunches. We think this is due to the fact that the coherent beam-beam effects are more pronounced for these bunches.

Figure 4 presents the spectra from the 21.4 MHz Schottky and the DTM spectra for selected bunches, at the end of the store #5186 measured with additional excitation of the beam. As expected, the spectra measured by the 21.4 MHz Schottky monitor (which does not distinguish between bunches) and by the DTM overlap.

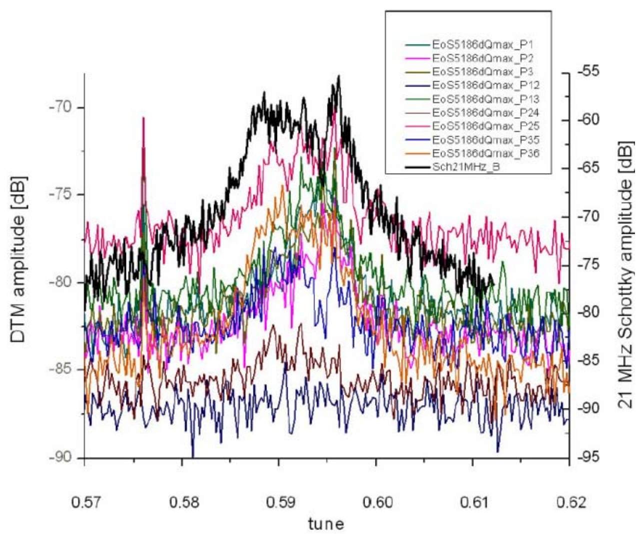

Figure 4: Spectrum from 21.4 MHz Schottky monitor and DTM (for selected proton bunches) measured at the end of the store # 5186.

FURTHER DEVELOPMENTS

A new beam excitation module is being developed for the DTM. Its purpose is to excite the beam for the period of time required for the DTM to take enough data to reconstruct the tunes with the required precision. This module can provide either white noise in a bandwidth from 0 to 200 kHz, a band limited noise or a swept sine wave from 15 to 20 kHz (around the tune frequency). This new device will excite the beam in horizontal and/or vertical planes with an output power in the order of few Watts. The synchronization between the DTM and the beam excitation module is presented in figure 5.

CONCLUSION

A Digital Tune Monitor based on 100 MHz 16 bits ADC was developed at Fermilab. Successful measurements of the vertical bunch-by-bunch proton tunes have been performed at the TEVATRON collider during HEP stores, with

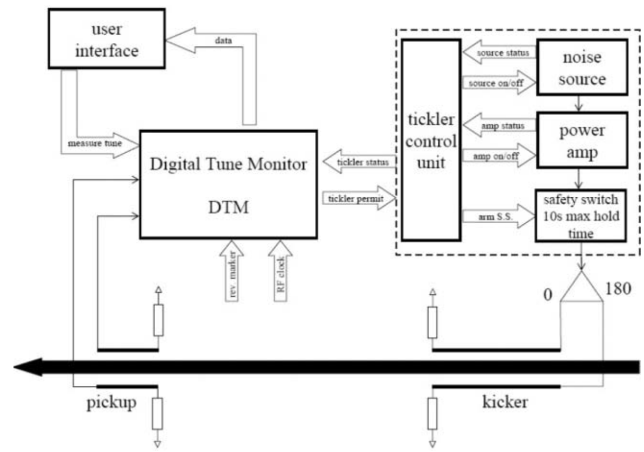

Figure 5: Schematic of the Digital Tune Monitor and Tickler.

a precision of $\sim 10^{-4}$, within ~ 2 seconds. External excitation of the proton beam was however necessary. It was shown that external excitation turned on for such a short period of time had no impact on collider operation. This monitor is now being installed in the TEVATRON ring to be used routinely as a tune monitor.

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