LONGITUDINAL BUNCH DYNAMICS IN THE TEVATRON

R. Moore, V. Balbekov, A. Jansson, V. Lebedev, K.Y. Ng, V. Shiltsev, C.Y. Tan
Fermi National Accelerator Laboratory, Batavia, IL, USA 60510

Abstract

We present our observations of the longitudinal bunch dynamics in Tevatron for uncoalesced proton bunches at 150 GeV and coalesced proton bunches at 150 GeV and 980 GeV. We have observed long-term (>15 minutes) coherent oscillations of uncoalesced protons that preserve already existing oscillations from upstream accelerators. A single-bunch instability in large intensity protons bunches at 980 GeV has also been observed.

UNCOALESCED PROTONS AT 150 GEV

Table 1 provides some relevant parameters of the Tevatron. A resistive wall monitor and a 2 GS/s digital oscilloscope are used to gather longitudinal profiles of the beam. Coherent synchrotron oscillations, originating in upstream accelerators, can be maintained for many (> 15) minutes in the Tevatron without an increase in longitudinal emittance. Uncoalesced protons are a train of 30 consecutive radiofrequency (RF) buckets populated with typically 10 E9 protons per bunch; this beam is used for machine tune-up, not colliding beam physics. Figure 1 illustrates the synchrotron oscillations of 3 bunches of uncoalesced protons over time at 150 GeV. We refer to this phenomenon as "dancing bunches" [1].

Table 1: Tevatron Parameters

Parameter	Value
Average radius	1000 m
Injection, Collision Energy	150, 980 GeV
RF frequency (period)	53.1 MHz (18.8 ns)
RF Voltage	1.1 MV
RF harmonic	1113
Synchrotron Freq. (150, 980 GeV)	86 Hz, 34 Hz
RF Bucket Area @ 150, 980 GeV	4.5, 11 eV-sec

Figure 2 shows a typical Fast Fourier Transform (FFT) of a typical bunch in an uncoalesced train. The sharp peak corresponds to a dipole oscillation at the synchrotron frequency of 86 Hz. There are no visible correlations in the amplitude or phase of the individual bunch oscillations (see Figure 3). Nevertheless, a weak coupling of the bunches probably exists since there is a slow amplitude modulation of the oscillations, as seen in Figure 1. The second, broader peak in Figure 2 with frequency about 260 Hz is not fully understood. We do know that this motion is coupled among all the bunches; Figure 4 shows the amplitude of this higher frequency oscillation is essentially the same for all bunches over the measurement period. In addition, the bunches oscillate in phase at this higher frequency, and this frequency actually decreases slowly over time. We believe this motion may be a driven oscillation, but the source of the driving force has not been identified.

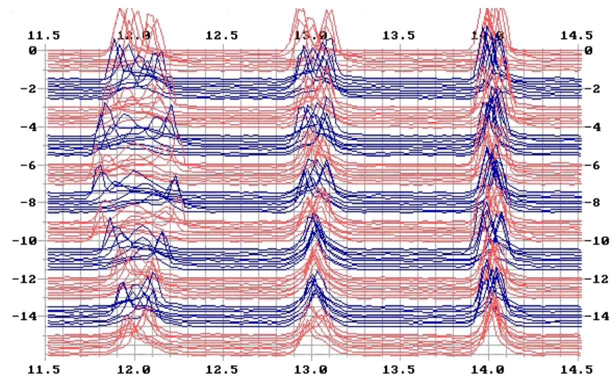

Figure 1: Longitudinal profile of bunches 12-14 of an uncoalesced proton train. Time (vertical axis, in minutes) progresses downward. Each colored band represents 0.9 sec of data; 40 turns (≈0.85 μs) separates individual traces. Each band is separated in time by 1.5 min.

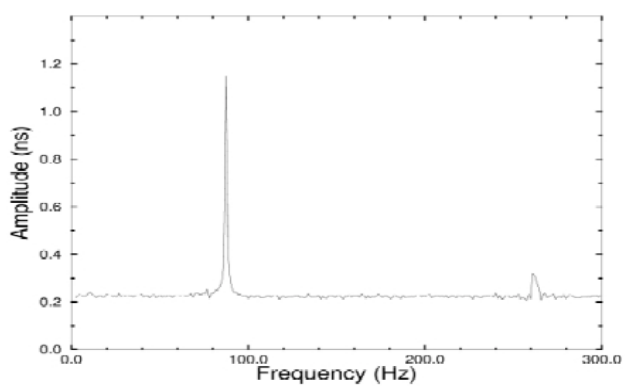

Figure 2: FFT of an oscillating proton bunch centroid.

An inductive impedance Z/n = i * const can explain how coherent synchrotron oscillations can survive for so long with little coupling among the bunches [2]. It does not affect coherent oscillations of a bunch centroid, but it does shift the oscillation frequency of individual particles around the center incoherently by an amount $\Delta\Omega$ which is proportional to $|Z/n|$. The condition when "dancing" should be observed can be expressed as $\Delta\Omega > \delta\Omega$ where $\delta\Omega$ is a synchrotron frequency spread. For the Tevatron at 150 GeV, the longitudinal impedance threshold allowing "dancing bunches" is $|Z/n|\ (\Omega) \sim 2{*}10^{11}\varphi^5/N \approx 1\Omega$, where $N = 10^{10}$ (number of protons per bunch), and $\varphi = 0.5$ (bunch half-length in RF radians). This impedance agrees well with the estimated longitudinal impedance value based on transverse impedance measurements [3].

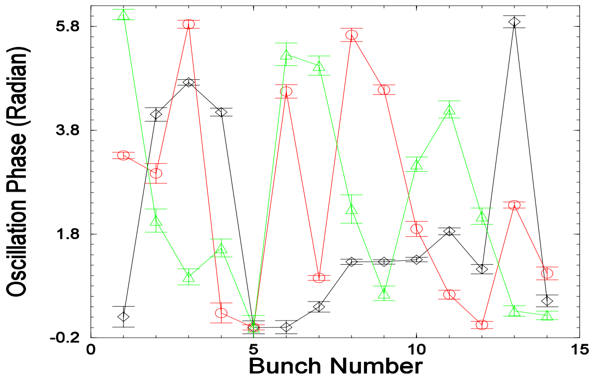

Figure 3: Oscillation phase of uncoalesced proton bunches. Black diamonds are 90 sec after injection; green triangles are 180 sec after injection; red circles are 820 sec after injection.

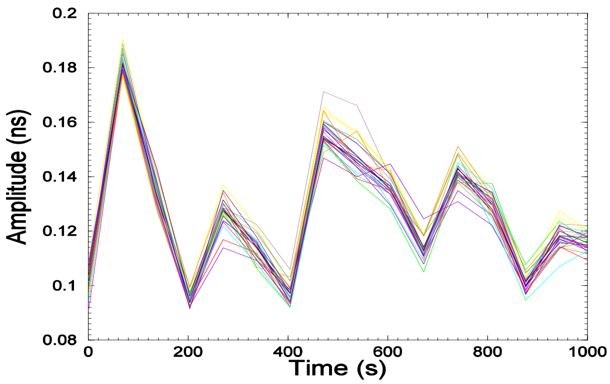

Figure 4: Amplitude of the higher-frequency oscillation versus time. Each color represents a different bunch.

COALESCED PROTONS AT 150 GEV

For colliding beam physics operation, the Tevatron is loaded with 36 coalesced proton and antiproton bunches. Coalescing occurs in the Main Injector at 150 GeV prior to injection into the Tevatron [4]. Typically 7 proton bunches are coalesced into a single bunch of 250-290 E9 protons. As seen in Figure 5, coalesced protons essentially fill a Tevatron RF bucket at 150 GeV. Typical RMS proton lengths in the Tevatron at injection are 3.1-3.3 ns; there is ~10% bunch length growth between the Main Injector and Tevatron, as shown in Figure 6. However, we observe longitudinal shaving in the Tevatron at 150 GeV; Figure 7 shows how the average RMS bunch length of the 36 proton bunches decreases.

One can also see in Figure 5 how coalesced protons can oscillate. These oscillations are remnants of the coalescing process, and they can persist for minutes in the Tevatron like the dancing uncoalesced bunches. Figure 8 depicts the longitudinal phase space distribution of the bunch shown in Figure 5; the distribution was reconstructed with longitudinal tomography code from CERN [5]*. The oscillating peaks seen in Figure 5 are also evident in Figure 8 as the off-center "hot spots" in the phase space distribution. An active, wideband longitudinal damper system [6] helps reduce these proton oscillations; the damper system is enabled only after all 36 proton bunches are injected.

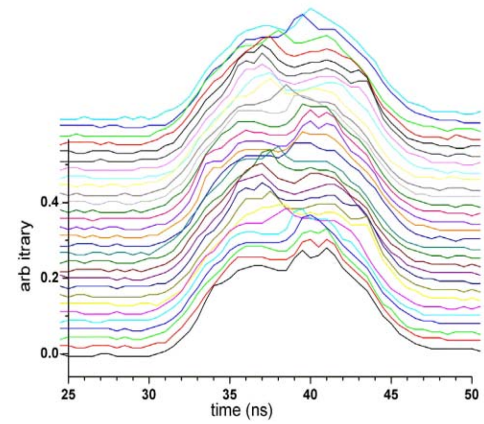

Figure 5: Profile of a coalesced proton bunch at injection in the Tevatron. Traces are separated in time (from bottom to top) by 40 Tevatron turns.

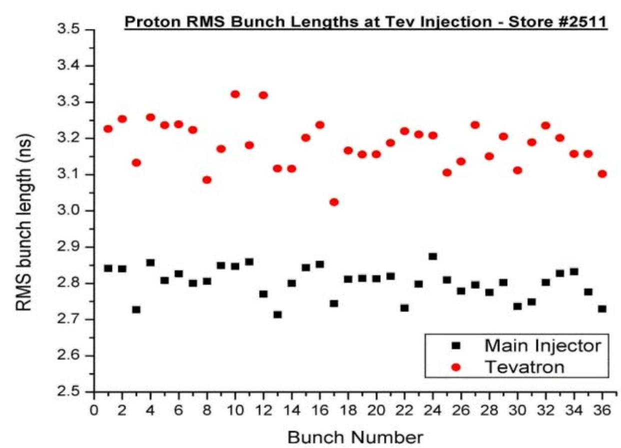

Figure 6: RMS bunch lengths of coalesced protons prior to extraction from the Main Injector (black squares) and after injection into the Tevatron (red circles).

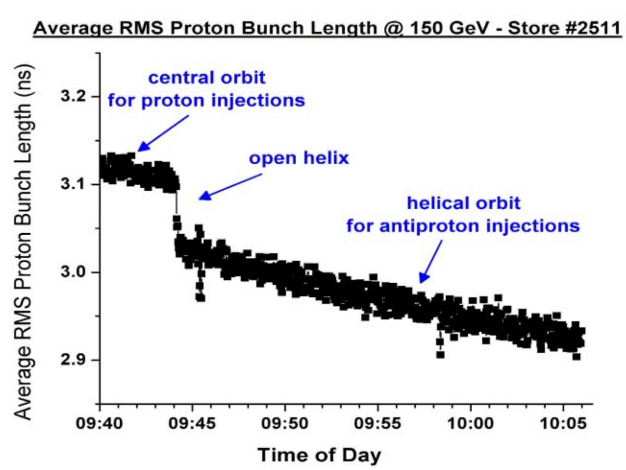

Figure 7: Coalesced protons experience longitudinal shaving while at 150 GeV.

* Although the code can handle space charge effect, this option was turned off for the reconstructions presented here.

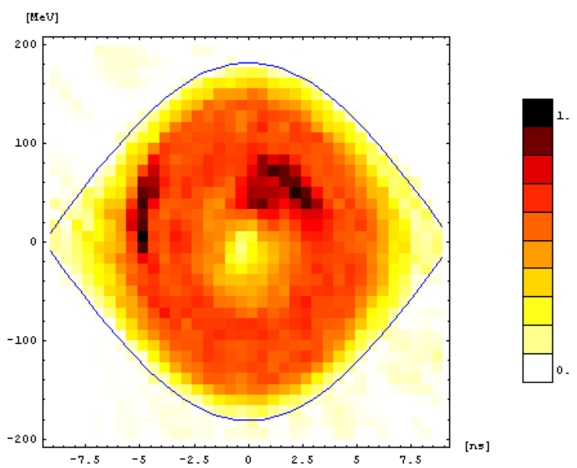

Figure 8: Reconstructed longitudinal phase space distribution of the coalesced proton bunch shown in Figure 5. Darker colors mean higher phase space density.

COALESCED PROTONS AT 980 GEV

After acceleration to 980 GeV, coalesced proton bunches are quite Gaussian and have no off-center "hot spots" in their longitudinal phase space distribution (See Figure 9 and Figure 10.) Once typical proton bunch intensities at 980 GeV reached ~150 E9, we began to observe single-bunch instabilities which would cause spontaneous bunch length growth with minimal beam loss in many, but not necessarily all bunches. However, the colliding beam luminosity would decrease as a result of the bunch length growth. (See Figure 11.) The previously mentioned longitudinal damper system has effectively eliminated this instability [6]. During HEP stores, the average proton RMS bunch length is 1.9-2.0 ns at the start of a store and grows at a rate of 0.03-0.06 ns/hr. Additional details about Tevatron emittance lifetimes in general can be found in [7].

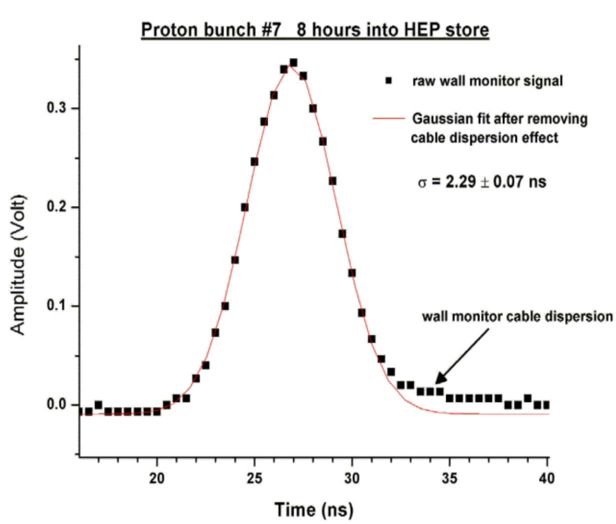

Figure 9: Longitudinal profile of a coalesced proton bunch at 980 GeV in the Tevatron.

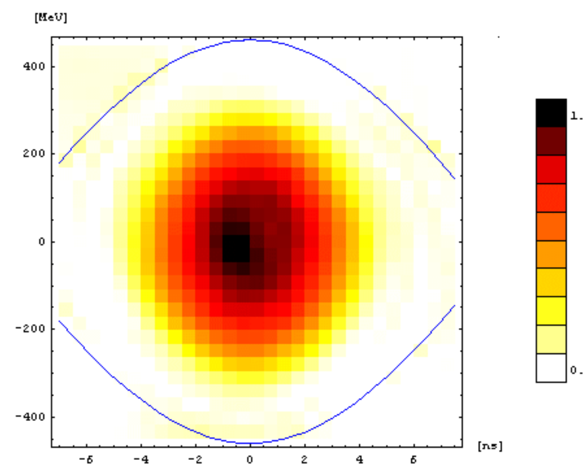

Figure 10: Reconstructed longitudinal phase space distribution of a coalesced proton bunch at 980 GeV.

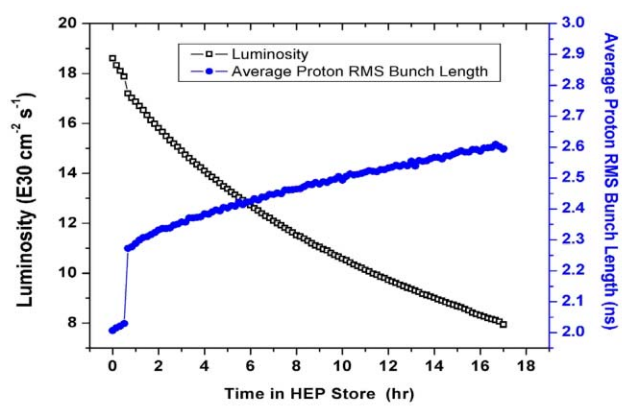

Figure 11: Illustration of proton bunch length blow-up and resulting decrease in luminosity during a high-energy physics (HEP) store in the Tevatron before longitudinal damper system was commissioned.

REFERENCES

[1] W. Guo, R. Moore, K. Y. Ng, S. Y. Lee, "Dancing Bunches at the Tevatron", Fermilab Technical Memo TM-2203, 2003.

[2] V. I. Balbekov and S. V. Ivanov, "Thresholds of Longitudinal Instability of Bunched Beam in the Presence of Dominant Inductive Impedance", IHEP-91-14, Protvino, 1991.

[3] P. Ivanov et al, "Head-Tail Instability at Tevatron", these proceedings (RPPB021).

[4] I. Kourbanis et al, "Performance of Main Injector Bunch Coalescing during Fermilab's Current Collider Run", these proceedings (RPAG021).

[5] S. Hancock, S. Koscielniak, M. Lindroos, Phys Rev ST-AB, Vol. 3, 124202 (2000).

[6] C.Y. Tan and J. Steimel, "The Tevatron Bunch By Bunch Longitudinal Dampers", these proceedings (RPPB024).

[7] P. Lebrun et al, "Observations on the Luminosity Lifetimes, Emittance Growth Factors and Intra-Beam Scattering at the Tevatron", these proceedings (TPPB062).