ALTERNATIVE BUNCH FORMATION FOR THE TEVATRON COLLIDER

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Abstract

Both the proton and antiproton bunches in the Fermilab Tevatron Collider have longitudinal emittances that are so large as to introduce serious limitations to operations. Poor beam lifetime, narrower horizontal aperture, and 30% lower luminosities are just a few examples. Theoretically, these 36 protons and 36 antiproton bunches could have longitudinal emittances roughly 6-10 times smaller if the formation of these bunches did not involve emittance dilution. In this paper, alternative longitudinal manipulations are discussed that reduce or eliminate this nonadiabatic longitudinal emittance growth. The measured results of accelerator studies in the Fermilab accelerator chain are presented and compared with theoretical and numerical calculations.

MOTIVATION

The formation of the 36 proton and 36 antiproton bunches required for Fermi National Accelerator Laboratory (Fermilab) Tevatron Collider operations [1] presently requires that several bunches spaced at 53 MHz are coalesced [2] into a single high intensity bunch with correspondingly large longitudinal emittance. It was proposed over six years ago to reduce the longitudinal emittance of antiproton bunches by directly transferring and accelerating antiprotons at a lower RF frequency until acceleration reduced the bunch length and increased the RF bucket area sufficiently to directly capture the beam in a single 53 MHz RF bucket. It is proposed in this paper to reduce the longitudinal emittance of the Collider proton bunches by performing an alternative coalescing scheme at injection of the Main Injector. Because of large coherent longitudinal oscillations in the bunches from the Booster ring [3], this alternative method is awaiting Booster beam improvements.

ANTIPROTON BUNCHES

Protons are injected from the Fermilab Booster into the Main Injector at a kinetic energy of 8 GeV. Antiprotons are injected at 8 GeV from either the Fermilab Accumulator or Recycler rings. The Main Injector accelerates both beams to 150 GeV for eventual injection into the Tevatron Collider.

The Tevatron Collider needs 36 antiproton bunches. At present the Accumulator ring performs 9 transfers of antiproton beam to the Main Injector, and Tevatron. Each transfer consists of 4 groups of between 7 and 11 bunches spaced at 53 MHz. This charge distribution is accelerated to 150 GeV and then coalesced [2] into 4 monolithic bunches and transferred into the Tevatron Collider. The 4 bunches each have a longitudinal emittance between 2 and 3 eV-sec, whereas the initial distributions extracted from the core of the Accumulator antiproton beam was 0.4-0.6 eV-sec. The longitudinal emittance dilution is suffered at the time the beam is bunched at 53 MHz in the Accumulator, and when the 53 MHz structure is again removed during the coalescing process.

The original reason for this arrangement was the fact that the old Main Ring synchrotron had a very limited longitudinal emittance aperture at transition. The new Main Injector ring has been shown during the work described in this paper to have a longitudinal acceptance in excess of 0.7 eV-sec. As described in the Recycler technical design report [4], it is possible to completely bypass the coalescing process by performing bucket-to-bucket transfers between the Accumulator (or Recycler) and Main Injector at 2.5 MHz. After some acceleration to get closer to transition, direct adiabatic transfer of beam from the 2.5 MHz RF system and the 53 MHz RF system can take place to form the Tevatron Collider bunches. In principle no longitudinal emittance growth is incurred in this scenario and a reduction of bunch length and momentum spread of more than a factor of two is realized. Such a reduction would significantly improve Collider operations.

PROTON BUNCHES

The goal of the research described in this paper was to generate proton bunches for the Tevatron Collider with longitudinal emittances less than 1 eV-sec. The tactic proposed to accomplish this goal was to perform the coalescing process on the Booster bunches at 8 GeV in the Main Injector just after injection. Traditional 150 GeV coalescing [2] incurs significant particle loss, and the concept for this alternative formation process is to invoke particle loss at the very beginning of the coalescing process in order to increase the phase space density of the initial Booster bunch distributions.

Simulation of the Process

The author wrote a multiparticle simulation using Microsoft Excel to assess numerically the viability of this alternative formation process. Using 7000 test particles to simulate 7 Booster bunches, the initial distribution was generated assuming a bi-Gaussian longitudinal phase space density distribution with a 95% invariant longitudinal emittance of 0.2 eV-sec per bunch. Figure 1 shows an example of such a distribution in phase space, where the vertical axis is fractional energy deviation and the horizontal axis is RF phase in radians.

The first step is to snap down the RF bucket height such that only the core of the bunch distribution is still within the bucket. As seen in figure 2, after 90 degrees of phase advance the distribution has lost the low density protons in one phase space dimension.

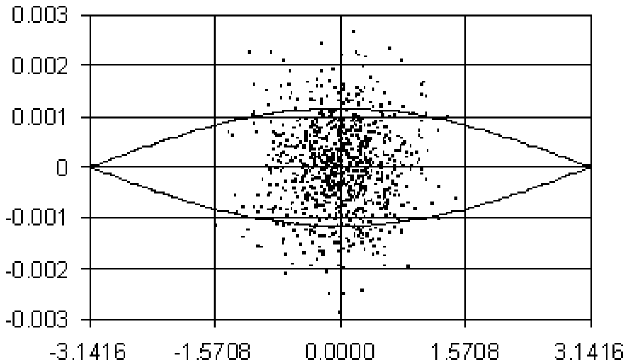

Figure 1: Initial distribution of the test particles in one of seven bunches simulating this alternative form of proton coalescing at 8 GeV in the Main Injector.

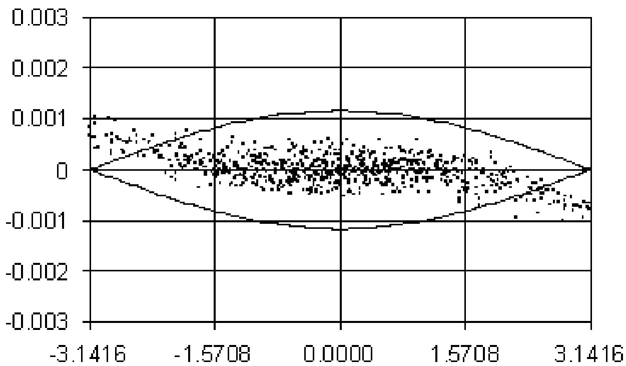

Figure 2: Distribution after 90 degrees of synchrotron phase advance in the RF bucket formed after instantaneously snapping down the RF voltage to 100 kV.

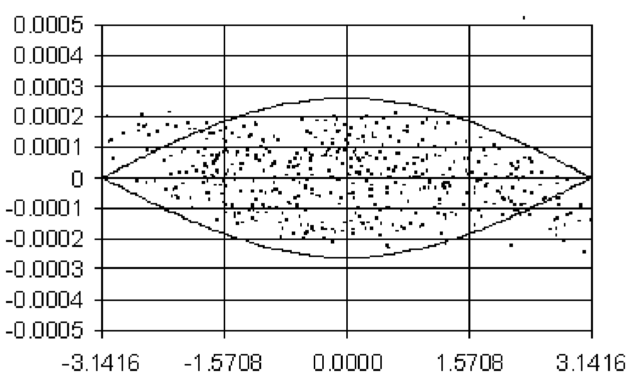

Figure 3: The result of stepping the RF voltage down to 5 kV and waiting another 90 degrees of synchrotron phase advance in the newly reduced RF bucket.

In order to cut away the low density protons in the other projection of phase space, the RF bucket height was again snapped down to bisect the energy distribution shown in figure 2. Figure 3 presents the result of waiting 90 degrees in synchrotron phase advance after this second voltage reduction. Note the reduction in energy spread as compared to figure 1. Figure 4 is an expanded view of the phase space distribution of the entire group of 7 Booster bunches. Note that the low density protons are streaming away while the dense distribution cores of the bunches form a high density line charge ready for coalescing with the Main Injector 2.5 MHz RF system.

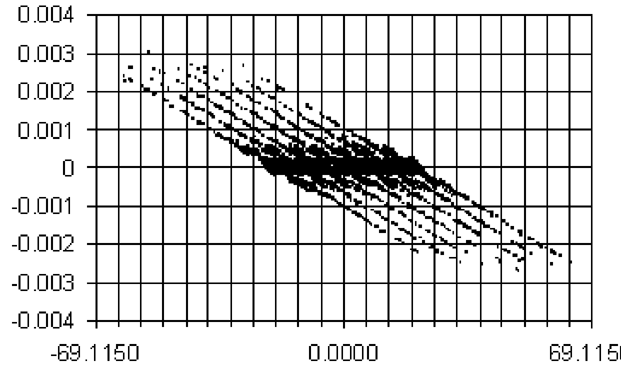

Figure 4: Expanded view of figure 3, showing the phase space distribution of all 7 Booster bunches. The dense central line charge is now ready for coalescing.

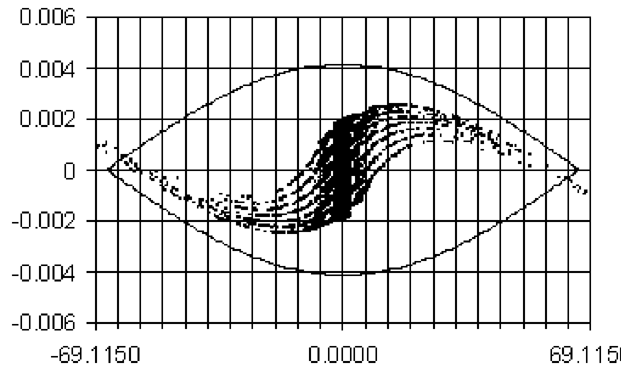

Figure 5: Phase space distribution of the protons after rotation in the 2.5 MHz RF system bucket by 90 degrees in synchrotron phase.

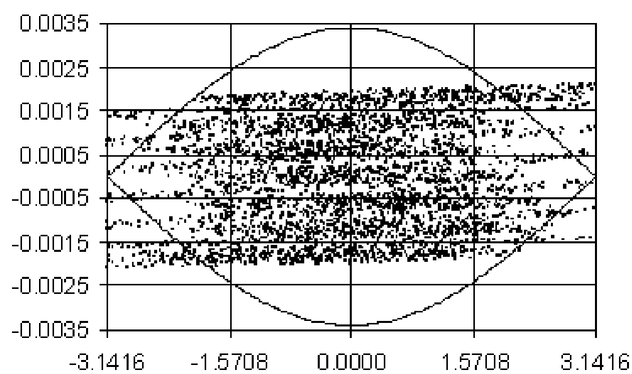

Figure 6: Same view as figure 5 but restricted to the central 53 MHz RF bucket that recaptures the beam for later synchronous transfer to the Tevatron Collider.

The 2.5 MHz RF system has a maximum voltage of 60 kV. In addition, there is a lower voltage 5.0 MHz system capable of partially linearizing the sinusoidal waveform in order to rotate up to 11 bunches uniformly. Figure 5 shows the effect of this RF system on the proton distribution after 90 degrees of synchrotron phase advance. At this stage the 2.5 MHz is turned off and 850 kV capture voltage at 53 MHz is snapped on.

Figure 6 shows the capture RF bucket superimposed on the central charge distribution shown in figure 5. Figure 7 shows the steady state charge distribution in the central bucket a few milliseconds after the recapture process.

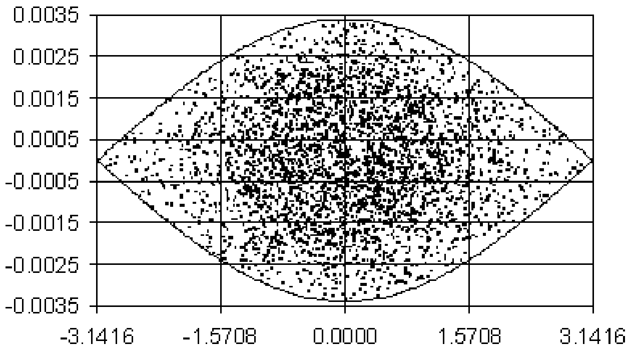

Figure 7: The distribution in figure 6 after a few milliseconds of storage in the 850 kV RF bucket.

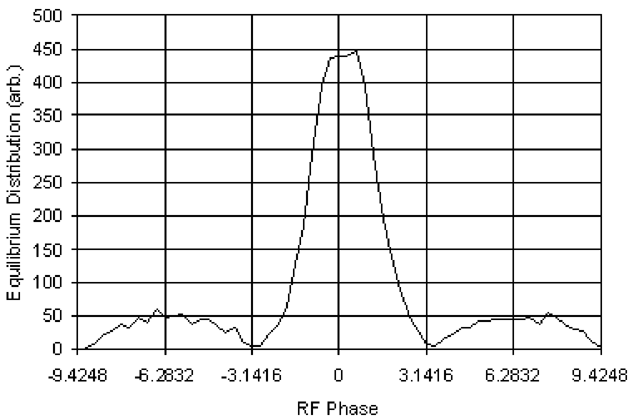

Figure 8: Histogram of the data in figure 7 simulating the longitudinal beam profile measured using a wall current monitor in the Main Injector. The central bunch plus the two neighboring RF buckets are shown.

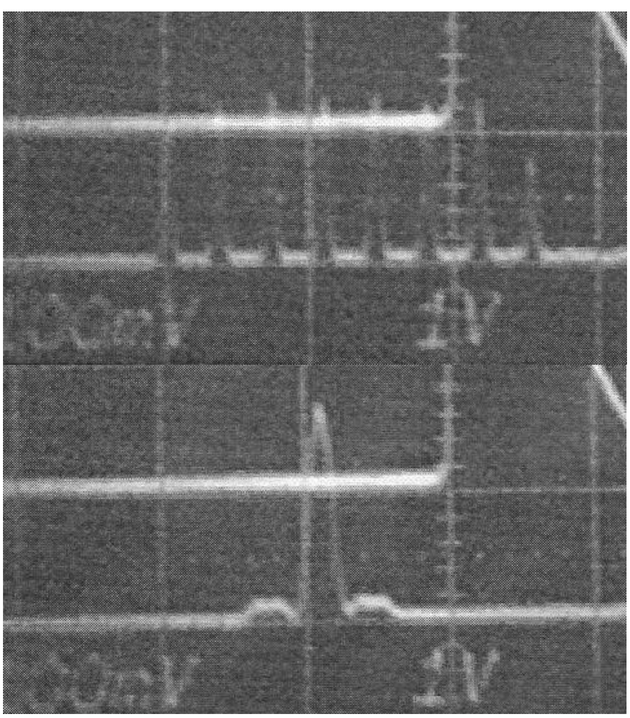

Figure 9: Measured beam profile after testing this alternative form of proton bunch formation at 8 GeV in the Fermilab Main Injector. Note the similarity to fig. 8.

Measurement of the Process

Figure 8 was generated by histogramming the RF phase coordinates of all the test particles trapped in the RF buckets. This alternative bunch formation process was tested in the Main Injector at 8 GeV using the same proton longitudinal emittance and RF voltages that were simulated. The measured beam profile using the Main Injector resistive wall detector is shown in figure 9. Note the accuracy with which the simulation predicted the final bunch shape for the core and satellite RF buckets.

Unfortunately, at higher intensities relevant for Tevatron Collider operations the reproducibility and accuracy of the simulation disappeared. It was noted that although the single bunch longitudinal emittance from the Booster had not increased with intensity, the size of the coherent longitudinal oscillations was dramatic. Figure 10 contains a measurement of such oscillations. Until these oscillations are reduced in the Booster, this alternative proton bunch formation scheme for the Tevatron Collider is not possible.

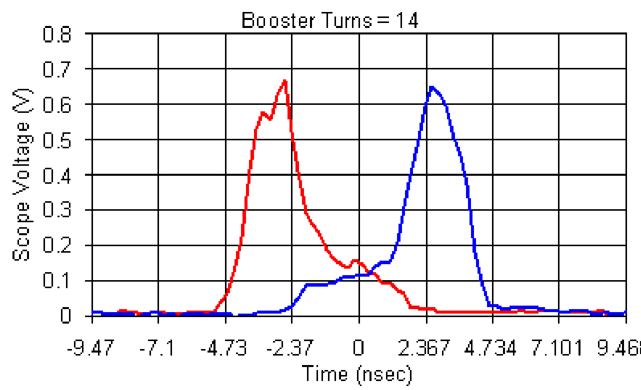

Figure 10: Same bunch measured twice separated by approximately one half synchrotron oscillation. The full width of the plot is an entire RF bucket.

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