EXPERIMENTAL TEST OF A NEW ANTIPROTON ACCELERATION SCHEME IN THE FERMILAB MAIN INJECTOR*

V. Wu, C. M. Bhat, B. E. Chase, J. E. Dey, K. G. Meisner,
FNAL, Batavia, IL 60510, U.S.A.

Abstract

In an effort to provide higher intensity and lower emittance antiproton beam to the Tevatron collider for high luminosity operation, a new Main Injector (MI) antiproton acceleration scheme has been developed [1-4]. In this scheme, beam is accelerated from 8 to 27 GeV using the 2.5 MHz rf system and from 27 to 150 GeV using the 53 MHz rf system. This paper reports the experimental results of beam study. Simulation results are reported in a different PAC'05 paper [5]. Experiments are conducted with proton beam from the Booster. Acceleration efficiency, emittance growth and beam harmonic transfer between 2.5 MHz (h=28) and 53 MHz (h=588) buckets have been studied. Beam study shows that one can achieve an overall acceleration efficiency of about 100%, longitudinal emittance growth less than 20% and negligible transverse emittance growth.

INTRODUCTION

The Fermilab Tevatron collider is a proton and antiproton facility dedicated for high energy physics research. In order to maximize the integrated luminosity delivered to the collider experiments, the beam intensity and the emittances through the accelerator chain need to be preserved as much as possible. The Main Injector, a 150 GeV synchrotron, serves as the injector to the Tevatron. Currently the antiproton bunches for Tevatron are produced by a multi-bunch coalescing scheme in the MI at 150 GeV [6]. This method yields about a factor of two increase in the longitudinal emittance and 5% to 20% decrease in intensity before injection to Tevatron. Most of the emittance growth and beam loss comes from the coalescing process. In an effort to improve emittance growth and beam loss, a new antiproton acceleration scheme, called 2.5 MHz acceleration for short, is developed. According to simulations [5], the new method can potentially reduce the emittance growth to the 10% level without beam loss.

The 2.5 MHz acceleration method uses both the Main Injector 2.5 MHz and 53 MHz rf systems for beam acceleration. Figure 1 shows a schematic view of the principle behind this method. At present, all of the antiproton injections to the MI are in 2.5 MHz buckets [7]. Therefore, it is natural to begin MI acceleration in 2.5 MHz buckets. Four 2.5 MHz bunches are accelerated through transition (about 20.4 GeV) from 8 to 27 GeV. At the constant energy 27 GeV, the bunches are transferred to 53 MHz buckets after two rotations. Then the beam is accelerated to 150 GeV and injected to the Tevatron. The multi-bunch coalescing process is eliminated in this acceleration scheme. Consequently, longitudinal emittance growth is reduced. Smaller emittance growth reduces beam loss.

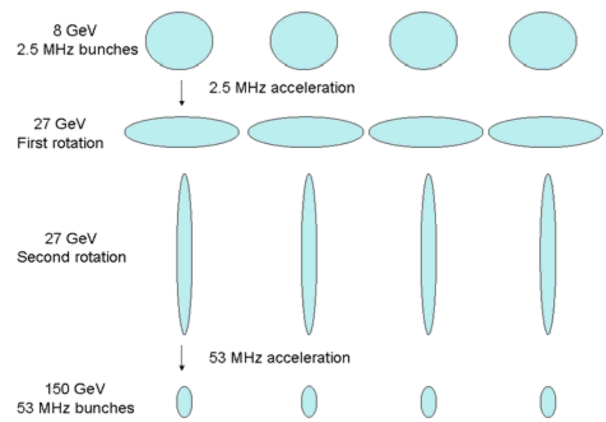

Figure 1: The 2.5 MHz acceleration scheme. The acceleration begins with four consecutive 2.5 MHz bunches. At 27 GeV, the bunches undergo two one quarter synchrotron period rotations. When the bunches are at minimum bunch widths at the end of the second rotation, they are transferred to matched 53 MHz buckets. Then the 53 MHz bunches are accelerated to 150 GeV and injected into the Tevatron.

EXPERIMENTS

Proton beam is used to test the feasibility of the 2.5 MHz acceleration scheme. The 2.5 MHz bunches are prepared in the MI at 8 GeV by injecting four short batches of 53 MHz bunches from the Fermilab Booster; see Fig. 2 for mountain range picture. These batches are spaced by twenty-one 53 MHz buckets (398 nsec apart) for creating four consecutive 2.5 MHz bunches. The numbers of Booster turn and 53 MHz bunches in each batch depend on the desired initial 2.5 MHz intensity and longitudinal emittance. After injection, the 53 MHz rf voltage is adiabatically reduced to debunch the 53 MHz bunches inside 2.5 MHz buckets. At the end of debunching, the high power inputs to the 53 MHz cavities are switched off. The measured total residual rf voltage in the 53 MHz cavities (due to bleed through problem) is of the order of 100 V [8]. Both 2.5 MHz and 53 MHz beam loading compensations are on during beam studies.

Once the 2.5 MHz bunches are prepared, they are accelerated from 8 to 27 GeV with the 2.5 MHz rf system and from 27 to 150 GeV with the 53 MHz rf system. Acceleration is performed with closed phase feed-forward

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#vincentw@fnal.gov

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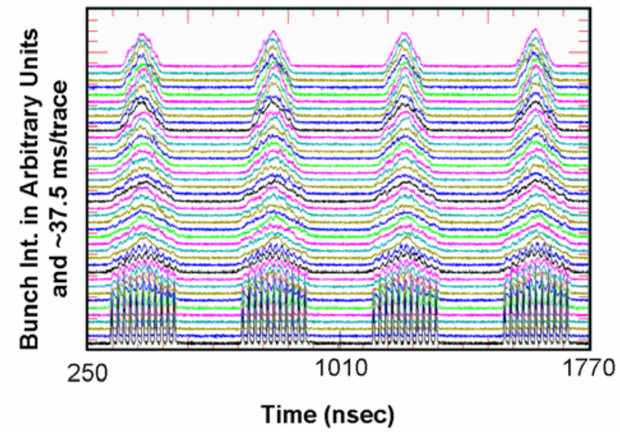

Figure 2: (Color) Mountain range picture showing the process of creating four 2.5 MHz bunches in the Main Injector at 8 GeV. In this case, 4 batches of 11 Booster proton bunches (53 MHz) are injected into the Main Injector. The 53 MHz bunches are adiabatically debunched inside 2.5 MHz buckets. Then the 2.5 MHz bunches are shrunk adiabatically prior to acceleration.

and radial position feedback loops. Since the acceleration involves two different frequencies, two sets of phase and radial position detectors and feedback loops are used. At the 27 GeV constant energy, the 2.5 MHz bunches undergo two one quarter synchrotron period rotations. The first rotation is at about 4 kV for reducing the bunch height to an acceptable level (a few MeV). The second rotation is a fast rotation at 60 kV. When the bunches are at minimum bunch widths (less than 18.9 nsec, the width of 53 MHz bucket), 53 MHz cavities are switched back on and capture the bunches with matched buckets. Figure 3 shows mountain range picture of the rotations and the beam harmonic transfers to 53 MHz buckets. After 53 MHz captures, the phase and the radial position loops switch from 2.5 MHz to 53 MHz before beam acceleration to 150 GeV.

Figure 4 shows the 150 GeV momentum ramp, the 2.5 MHz and the 53 MHz rf amplitude curves and the beam intensity for the case of initial bunch intensity 60×10^9 and bunch emittance 2 eVs. The slow acceleration (2.5 MHz) portion of the ramp has a maximum dP/dt of 3.2 (GeV/c)/sec. (At the moment, the maximum dP/dt can be used for 2.5 MHz acceleration is limited by maximum available 2.5 MHz rf voltage of 75kV.) For the fast acceleration (53 MHz), the maximum acceleration rate is 120 (GeV/c)/sec. The acceleration efficiency of the beam shown here from 8 to 27 GeV is 100% and from 27 to 150 GeV is about 98%. Overall, the 53 MHz capture efficiency is in the range of 90% to 100%.

The longitudinal emittance [9] of the beam at injection and at flat-top (150 GeV) are determined by measuring the bunch lengths and the rf voltages. The bunch emittance is calculated when the beam is in matched stationary bucket. Table 1 lists the measured longitudinal

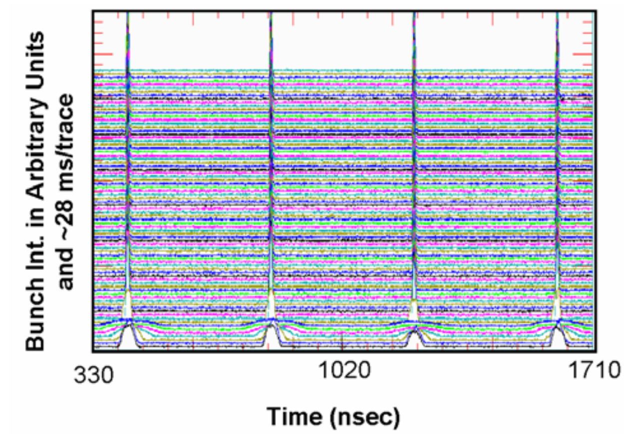

Figure 3: (Color) Mountain range picture showing the rotations and the beam harmonic transfer to 53 MHz buckets at 27 GeV. After 53 MHz captures, the bunches are accelerated to 150 GeV.

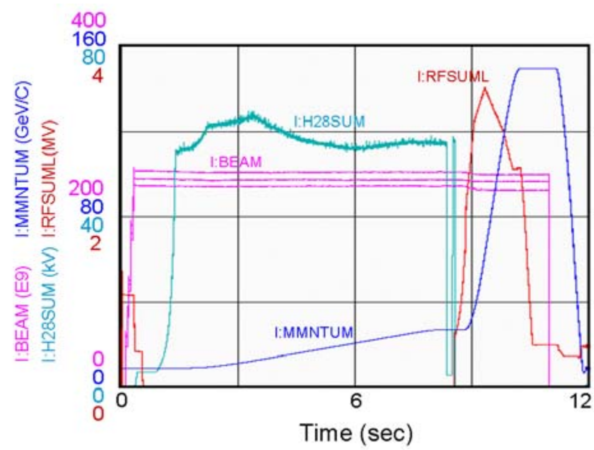

Figure 4: (Color) The 150 GeV momentum ramp (I:MMNTUM, blue), 2.5 MHz (I:H28SUM, green) and 53 MHz (I:RFSUM, red) rf curves and the beam intensity (I:BEAM, 10^9, pink) vs. cycle time (sec) for four batch injections. The total intensity is about 24×10^{10}. The acceleration efficiency is about 98%.

emittance for two cases of initial emittance and intensity. The 95% longitudinal emittance is calculated using the bunch length that corresponds to 95% of the area (total bunch intensity) under the Wall Current Monitor bunch signal. For the measurements, the operational parameters, *viz*., rotation voltages and time, 53 MHz capture time, 2.5 MHz alignment, etc., are tuned up for the case of 2 eVs initial emittance. Thus, the case of 0.9 eVs initial emittance is not optimized and has more emittance growth. For the optimized case, the amount of longitudinal emittance growth and the acceleration efficiency are consistent with the simulations.

Table 1: Longitudinal emittance (95%) measurements at injection and at 150 GeV flat-top for four batches injection. Measurement error is 10 to 20 percents.

Total Intensity (10^9)	130	240
Initial 8 GeV Emittance (eVs)/bunch	0.9	2.0
150 GeV Emittance (eVs)/bunch	1.5	2.2
Emittance Growth (%)	61	13
Overall Beam Loss (%)	1	8

The longitudinal emittance growth comes from two places, namely, transition crossing and rf manipulations at 27 GeV. Because of the relatively long transition region (about 150 ms for the non-adiabatic and non-linear regions), there is always a certain amount of beam mismatch to bucket after transition crossing. Bunch shape oscillation is observed after transition crossing (see Fig. 5) that leads to emittance growth. At 27 GeV, imperfect tuning in rotation voltages and timings, 2.5 MHz alignment, 53 MHz capture voltage, beam loading compensations, etc., can lead to emittance growth.

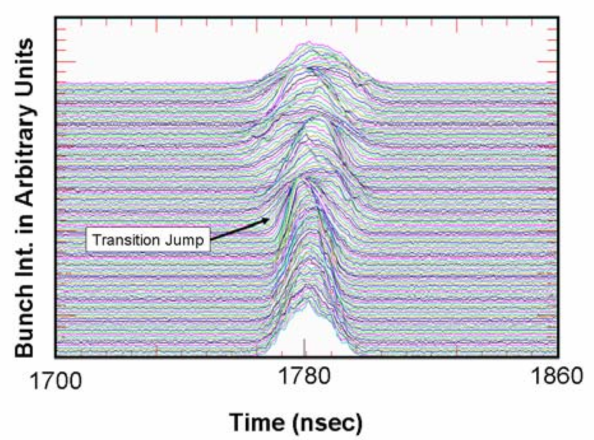

Figure 5: (Color) Mountain range picture showing transition crossing. Bunch shape oscillation is observed after transition jump which leads to emittance growth.

The transverse emittances of the beam are measured using the flying wires at various times up the ramp. Figure 6 shows typical flying wire data taken at 8 and 150 GeV. The measured transverse emittances are 8.9 π·mm·mr (vertical) and 9 π·mm·mr (horizontal) at 8 GeV and are 9.8 π·mm·mr (vertical) and 10.1 π·mm·mr (horizontal) at 150 GeV with about 10% measurement error. Thus, the transverse emittance growth is negligible.

CONCLUSIONS

A new antiproton acceleration scheme for producing high intensity and low emittance bunches for the Tevatron collider is presented. Experimental test of the acceleration scheme is carried out in the Main Injector using proton beam from the Booster. Beam study results are very promising. The longitudinal emittance growth is less than 20% and there is negligible transverse emittance growth. The overall acceleration efficiency is about 100 percents.

In the future, we plan to implement this scheme for antiproton acceleration in the MI for the Tevatron shots and expect about 5-10% higher instantaneous proton-antiproton luminosity at the collider detectors.

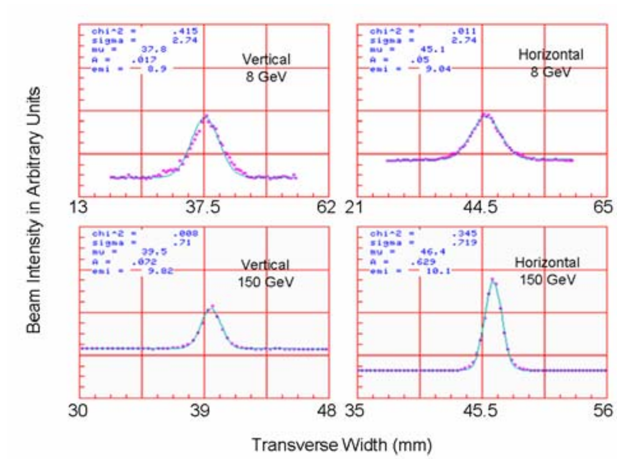

Figure 6: (Color) Transverse emittance measurements at 8 and 150 GeV using flying wires. The four plots show the vertical beam profiles (on the left) and the horizontal beam profiles (on the right). The overall transverse emittance growths in both planes are about 1 π·mm·mr.

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