SIMULATIONS OF AN ACCELERATION SCHEME FOR PRODUCING HIGH INTENSITY AND LOW EMITTANCE ANTIPROTON BEAM FOR FERMILAB COLLIDER OPERATION*

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Abstract

During Fermilab collider operation, the Main Injector (MI) provides high intensity and low emittance proton and antiproton beams for the Tevatron. The present coalescing scheme for antiprotons in the Main Injector yields about a factor of two increase in the longitudinal emittance and a factor of 5% to 20% decrease in intensity before injection to the Tevatron. In order to maximize the integrated luminosity delivered to the collider experiments, it is important to minimize the emittance growth and maximize the intensity of the MI beam. To this end, a new scheme using a combination of 2.5 MHz and 53 MHz accelerations has been developed and tested. This paper describes the full simulation of the new acceleration scheme, taking account of space charge, 2.5 MHz and 53 MHz beam loading, and the effect of residual 53 MHz rf voltage during 2.5 MHz acceleration and rf manipulations. The simulations show the longitudinal emittance growth at the 10% level with no beam loss. The experimental test of the new scheme is reported in another PAC05 paper.

INTRODUCTION

The Fermilab Tevatron is the highest energy proton and antiproton collider in the world, dedicated to the research on the fundamental constituents of matter. The primary goal of the Fermilab Run II upgrade plan [1, 2] is to maximize the integrated luminosity delivered to the Tevatron collider experiments at CDF and D0. To achieve high luminosity, it is essential to preserve the beam emittance and intensity through the accelerator chain. In this effort, beam acceleration and related rf manipulations in the Main Injector play prime role.

Currently, high intensity antiproton bunches in the Main Injector are produced by a multi-bunch coalescing process of 53 MHz bunches at 150 GeV [3]. Four consecutive 2.5 MHz antiproton bunches are injected into the Main Injector from either the Accumulator or the Recycler. Prior to acceleration, each antiproton bunch is adiabatically shrunk and then rebunched into five to nine 53 MHz bunches. The 53 MHz bunches are accelerated from 8 to 150 GeV. At 150 GeV, each group of antiproton bunches is coalesced into one 53 MHz bunch and then injected into the Tevatron. The coalescing process alone is found to introduce about a factor of two longitudinal emittance growth. The amount of beam loss is in the range of 5 to 20 percent depending on the initial bunch emittance and intensity. This longitudinal emittance growth can be reduced to the 10% level with no beam loss using a combination of 2.5 MHz and 53 MHz accelerations [1, 4-6] in the Main Injector.

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ANTIPROTON ACCELERATION USING 2.5 MHZ (H=28) AND 53 MHZ (H=588) RF SYSTEMS

Acceleration Scheme

The antiproton transfers to the Main Injector are in 2.5 MHz buckets and the longitudinal emittance is in the range of 0.8 (from Accumulator) to 3 eVs (Recycler). Hence, it is natural to begin acceleration in 2.5 MHz buckets. This eliminates the rf manipulations in 53 MHz prior to the acceleration and the associated emittance growth. Currently, the maximum dP/dt for 2.5 MHz acceleration in the Main Injector is limited by the available rf voltage of 75 kV for the 2.5 MHz rf system. Therefore, we accelerate the beam from 8 GeV to 150 GeV in two steps. From 8 to 27 GeV, four consecutive 2.5 MHz bunches are accelerated through transition (at about 20.4 GeV) using the 2.5 MHz rf system and a slow acceleration ramp with a maximum dP/dt of 3.2 (GeV/c)/s. For a 3 eVs bunch (Recycler beam), the $\Delta P/P$ is about $\pm 0.45\%$, which is about 40% smaller than the momentum acceptance of the MI at transition energy (about $\pm 0.7\%$). This allows us to accelerate bunches with longitudinal emittance up to about 4 eVs without any beam loss through transition. From 27 to 150 GeV, the beam is accelerated with the 53 MHz rf system.

Beam harmonic transfer between the 2.5 MHz and the 53 MHz buckets at constant energy 27 GeV are carried out with two one quarter synchrotron period rotations by the 2.5 MHz rf system. The first rotation is done at low voltage (a few kV) to reduce the bunch height to an acceptable level (a few MeV). Then a fast rotation at high voltage (60 kV) follows. When the bunches are at minimum bunch widths (less than 18.9 nsec, the width of 53 MHz bucket), they are captured in matched 53 MHz buckets. In addition to the 2.5 MHz voltages, second harmonic (h=56) voltages are added to linearize the quarter synchrotron period rotations. For the first and the second rotations, about 10% and 16% of the second harmonic are added, respectively. This reduces emittance dilution due to non-linearity in the rf wave form for large emittance beam.

Multiparticle Beam Dynamics Simulations

Longitudinal beam dynamics simulations are performed with a macro-particle Monte Carlo tracking code ESME [7]. The simulations are performed for the following cases: (1) space charge effect and broadband impedance, (2) with and without beam loading compensation on the 2.5 MHz rf system and (3) with and without beam loading compensation on the 53 MHz rf system. Simulations were also carried out to understand the effect of the 53 MHz rf voltage on the beam during 2.5 MHz acceleration and during the rf manipulations at 27 GeV.

The acceleration scheme is first simulated without the effects of space charge, beam loading and 53 MHz rf voltage to provide a reference for minimum emittance growth for the ideal situation. Figure 1 shows some phase

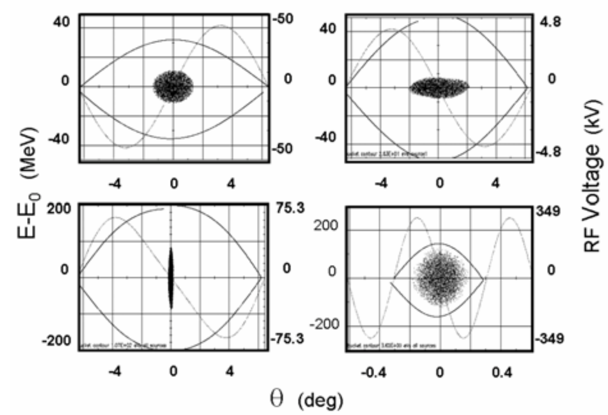

Figure 1: Phase space (ΔE, θ) distributions from 8 to 150 GeV. First plot is 2.5 MHz bunch at injection. Second plot is the end of first rotation at 27 GeV at minimum bunch height. Third plot is the end of second rotation at 27 GeV at minimum bunch width. Fourth plot is the 53 MHz bunch at 150 GeV.

space plots of the simulation. Transition crossing is performed simply by jumping the acceleration phase from the positive slope to the negative slope of the sinusoidal rf wave form. There is about 3% emittance growth for a 1.5 eVs beam bunch crossing transition. During the harmonic beam transfer at 27 GeV, the rf manipulations give about 5% emittance growth. The overall acceleration efficiency is 100%.

The effects of space charge and beam pipe coupling impedance on the beam are simulated with a single bunch. The beam pipe is assumed to be a broadband resonator. The estimated Main Injector longitudinal impedance per harmonic $Z_{||}/n$ = 1.6 Ω [8] is used. Generally, space charge is more problematic on low longitudinal emittance beam with high intensity. Therefore, simulation is performed for the case of 0.8 eVs initial emittance and 170×10^9 bunch intensity. Simulation shows that there is less than 10% overall emittance growth without beam loss. Further simulations show that there is no significant (less than 20%) emittance growth within a factor of three of $Z_{||}/n$ = 1.6 Ω.

For the simulations with 2.5 MHz beam loading, four bunches and one cavity are modeled in ESME. The Main Injector has five 2.5 MHz cavities. The shunt impedance of the cavity is increased by a factor of five to simulate the total beam loading. Simulations predict a significant amount of phase shift and filamentation to the bunches, which resulted in a considerable amount of emittance dilution as well as beam loss. Figure 2 shows the beam

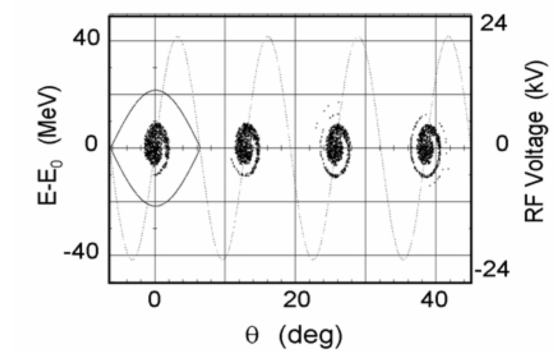

Figure 2: Phase space (ΔE, θ) distribution showing the effect of 2.5 MHz beam loading at injection.

loading effect. Undesirable effects on the bunches are first seen at 8 GeV when the 2.5 MHz voltage is small and comparable to the beam loading voltage. At the constant energy 27 GeV, the accumulated phase shift due to beam loading is rather large, e.g., more than 45 degrees. This creates severe bucket mismatch when the beam is transferred to the 53 MHz buckets. The maximum 2.5 MHz beam loading voltage is about 2.1 kV. In conclusion, 2.5 MHz beam loading compensation (BLC) is needed.

The physical effects of the feed-back BLC and the feed-forward BLC are to lower the quality factor (Q) of the cavity and to reduce the beam loading voltage, respectively. Therefore, the amount of required beam loading compensations can be estimated by reducing the cavity Q and the charge of the beam in the simulations. Simulations assuming a factor of 5 reduction in the cavity Q and a factor of 10 reduction in the beam charge are performed. Three cases of initial emittance, i.e., 0.8, 1.5 and 2.2 eVs with nominal bunch intensity 170×10^9 are studied. For the cases of 1.5 and 2.2 eVs, beam loadings are not problematic. The case of 0.8 eVs shows that the emittance growth of the last bunch is about seven times larger than that of the first bunch. This indicates that more beam loading compensation is needed for this case. To reduce the emittance growth to the 10% level, a factor of 30 reduction in the beam loading voltage from the feed-forward BLC is needed.

The Main Injector has eighteen 53 MHz cavities with a shunt impedance of 520 kΩ and a quality factor of 5000. The beam loading effects of these cavities on the beam can't be ignored. During the 2.5 MHz acceleration, 53 MHz beam loading can potentially affect the beam during transition crossing because the 2.5 MHz bunches at transition have time structures similar to those of the 53 MHz. Also, at 27 GeV, 53 MHz beam loading may

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affect the bunch rotations and the harmonic transfers to the 53 MHz buckets.

The effects of 53 MHz beam loading on the beam are simulated with four bunches and one cavity. The shunt impedance of the cavity is multiplied by a factor of 18 to simulate beam loadings of the 18 cavities. Simulation with bunch intensity of 60×10^9 and initial emittance of 1.5 eVs indicates that 53 MHz beam loading has adverse effects on the beam. The beam loading voltage causes fragmentation of the bunches when crossing transition. See figure 3. This resulted in large emittance dilution and beam loss when the bunches are transferred to 53 MHz buckets at 27 GeV. During 2.5 MHz acceleration, the beam loading voltage reaches a maximum of 12 kV at transition. The peak beam loading voltage during 53 MHz acceleration is 35 kV. In conclusion, 53 MHz beam loading compensation is required.

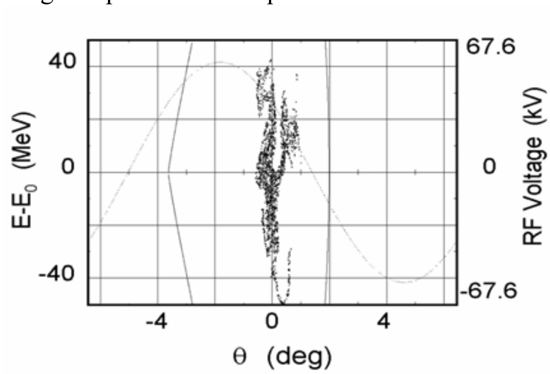

Figure 3: Simulation with 53 MHz beam loading during 2.5 MHz acceleration. Phase space (ΔE, θ) plot shows the first bunch after transition.

Simulations with 53 MHz beam loading assuming a factor of 5 reduction in the cavity Q and a factor of 10 reduction in the beam charge are performed. Two cases of bunch intensity, 60×10^9 and 170×10^9, with initial emittance of 1.5 eVs are studied. Simulation shows that beam loading in the case of bunch intensity 60×10^9 is insignificant. For the case of 170×10^9, the emittance growth of the last bunch is three times larger than that of the first bunch. To reduce the emittance growth of the last bunch to the 10% level, the feedforward BLC needs to provide a factor of 30 reduction in the beam loading voltage.

During the 2.5 MHz acceleration from 8 to 27 GeV, it is undesirable to short the Main Injector 53 MHz rf cavities. The 53 MHz rf systems need to be in tune with the MI magnet ramp so that at 27 GeV they can be turned on smoothly when the 2.5 MHz bunches are transferred to 53 MHz buckets. However, keeping the 53 MHz rf systems at low voltage during 2.5 MHz acceleration may cause transition crossing problem and filamentation to the 2.5 MHz bunches because of the 53 MHz modulation to the 2.5 MHz rf wave form. Therefore, the effect of the 53 MHz voltage on 2.5 MHz acceleration needs to be studied.

To understand this effect, a series of single bunch simulations are performed with various amount of constant 53 MHz rf wave superimposed on the 2.5 MHz accelerating rf wave form. Simulations show that the bunch behaves fairly well before transition. However, with high enough 53 MHz voltage, filamentation of the bunch occurs after transition crossing. The higher momentum particles are separated from the core and formed two spiral arms. During the first rotation (with 4 kV of 2.5 MHz voltage) at 27 GeV, the bunch develops 53 MHz structure as expected. Subsequently, this creates significant amounts of emittance growth and beam loss. The 53 MHz voltage during 2.5 MHz acceleration needs to be reduced to 500 V or less in order to have emittance dilution at the 10% level.

CONCLUSION

We need 2.5 MHz and 53 MHz feed-back and feed-forward beam loading compensations in order to keep emittance growth less than 20% with no beam loss. The minimal requirements for the 2.5 MHz and the 53 MHz beam loading compensations are a factor of 5 reduction in the cavity Q from the feed-back BLC and a factor of 10 reduction in the beam loading voltage from the feed-forward BLC. For small emittance (e.g., 0.8 eVs) and large bunch intensity (e.g., 170×10^9) beam, the requirements for the 2.5 MHz and the 53 MHz feed-forward BLC are a factor of 30 reduction in the beam loading voltage. The limit on the 53 MHz rf voltage during 2.5 MHz acceleration and bunch rotations is 500 V or less. The effects of the space charge and the beam pipe coupling impedance on the beam are insignificant.

REFERENCES

[1] G. P. Jackson, Fermilab Recycler Ring Technical Design Report, FERMILAB-TM-1991, November 1996.

[2] "Fermilab Collider Run II: Accelerator Status and Upgrades", P. C. Bhat and W. J. Spalding, to be published in the Proceedings of HCP2004, Michigan; "The Run II Luminosity Upgrade at the Fermilab Tevatron – Project Plan and Resources-Loaded Schedule", Internal Accelerator Division Document, June 2003.

[3] J. E. Griffin et al, IEEE, Trans. Nucl., Sci., **NS-30**, No. 4, (1983) 2627; C. M. Bhat et al, this proceedings.

[4] I. Kourbanis and D. W. Wildman, PAC1999, New York (1999), page 2840.

[5] J. A. MacLachlan, FERMILAB-TM-2177, July 2002.

[6] C. M. Bhat and J. E. Dey, "Pbar Acceleration in MI using 2.5 MHz Coalescing RF system – Tune-up Study Scheme with Proton Beam and Operational Implementation", MI Note 272, February 2001.

[7] J. A. MacLachlan, User's Guide to ESME 2002, Fermilab, November 2002.

[8] W. Chou, PAC1997, Vancouver, Canada (1997), page 991.