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ANTIPROTON ACCELERATION IN THE FERMILAB MAIN INJECTOR USING 2.5 MHZ (H=28) AND 53 MHZ (H=588) RF SYSTEMS

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Abstract

During the Run II era at Fermilab, the Recycler stores antiprotons at 8 GeV and the Main Injector accelerates the antiprotons and the protons from 8 GeV to 150 GeV for Tevatron injection. The Recycler injects antiprotons to the Main Injector in 2.5 MHz rf buckets. This report presents an acceleration scheme for the antiprotons that involves a slow ramp with initial 2.5 MHz acceleration and subsequent fast acceleration with 53 MHz rf system. Beam acceleration and rf manipulation with space charge and beam loading effects are simulated using the longitudinal simulation code ESME [1]. Simulation suggests that one can expect about 15% emittance growth for the entire acceleration cycle with beam loading compensations. Preliminary experimental results with proton beam will also be presented.

1 INTRODUCTION

In Run II, four antiproton bunches from the Recycler will be accelerated in the Main Injector from 8 GeV to 150 GeV. Antiproton transfer from the Recycler to the Main Injector is envisioned as 2.5 MHz bucket to bucket transfer to eliminate injection mismatch. An acceleration scheme with a slow ramp (2.5 MHz acceleration) followed by a fast ramp (53 MHz acceleration) was previously developed. (See references [2, 3, 4].) The simulations in this report follow a similar track as those of reference [3] and [4] with the inclusions of space charge and beam loading effects.

2 SIMULATIONS

The Main Injector accepts antiproton bunches from the Recycler with the following initial beam and rf parameters:

- Total beam energy: 8.938 GeV
- Rf frequency: 2.5 MHz
- Rf voltage: 2 kV
- Invariant 95% longitudinal emittance per bunch: 1.5 eVs
- Number of particles per bunch: 6×10^{10}.

The maximum accelerating rf voltages are 60 kV for the 2.5 MHz system and 4 MV for the 53 MHz system.

The ramp curve is shown in Fig. 1. The minimum ramp time is determined primarily by the maximum available 2.5 MHz rf voltage and the heating of the ferrite loaded 2.5 MHz cavities. The parabolic ramp begins at 0.5 second (8 GeV) and stops at 6.2 second (27 GeV front porch) where the transfer to 53 MHz system occurs. After 53 MHz capture, the beam is accelerated to 150 GeV in about 1.8 seconds.

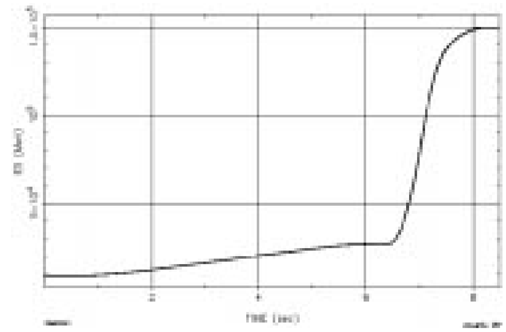

Figure 1: Ramp curve. The slope of the ramp increases to 4 GeV/s at 2 second and remains constant until 5.2 second where it ramps down to zero at 27 GeV. dP/dt during 53 MHz acceleration is about 190 GeV/c/s.

The rf programs for the 2.5 MHz and the 53 MHz accelerations are shown in Fig. 2 and 3, respectively. For

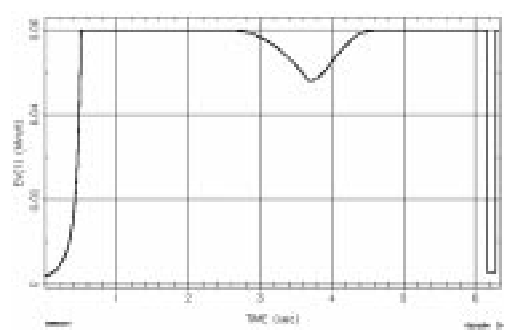

Figure 2: Voltage program for 2.5 MHz acceleration.

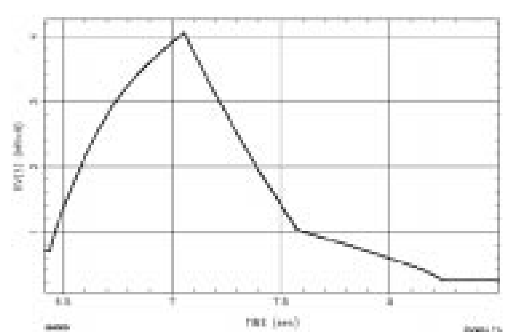

Figure 3: Voltage program for 53 MHz acceleration.

the first 0.5 second, the bunches are adiabatically shrunk by increasing the rf voltage to 60 kV. Because of the lack of phase focusing at transition, the rf voltage is lowered before transition to reduce the energy spread. This maneuver eases the problem of emittance dilution due to transition crossing. The rms emittance dilution for crossing transition is about 3%. At the 27 GeV front porch, the rf voltage drops to 3 kV (or 4 kV) and the bunches are rotated to minimum height with a second harmonic linearizing voltage. Then the h=28 and h=56 voltages are jumped to 60 kV and 10 kV respectively for a quarter period rotation to minimum width. The bunches are captured with the h=588 buckets of 700 kV voltage.

The acceleration and rf manipulation are first simulated without space charge and beam loading for a single bunch. Some pictures of the time evolution of the phase space distribution are shown in Fig. 4. The overall 95% emittance

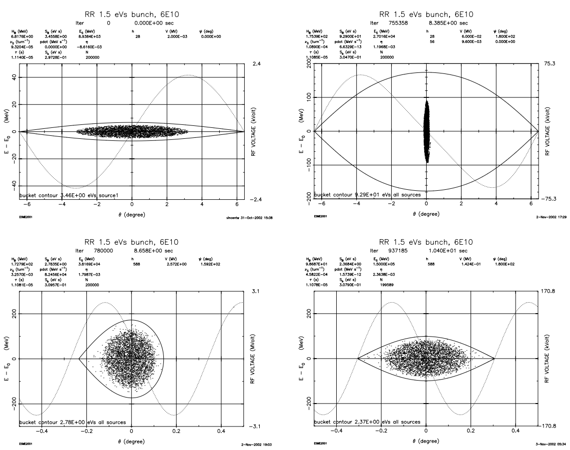

Figure 4: Time evolution of phase space distribution. Top left: Initial distribution. Top right: At the end of quarter synchrotron rotation. Bottom left: Accelerating bunch (53 MHz). Bottom right: Final distribution.

growth is 4% and no particles are lost.

The antiproton bunch intensity is about a factor of 10 smaller than typical Main Injector operation. However, because of the unusually long ramp, simulation with space charge is carried out to check emittance dilution. The effects of beam space charge and coupling impedance between the beam and the beam pipe are simulated with the following input parameters:

- Assume circular beam pipe as a broadband resonator (Q=1) with 1.7 GHz cutoff frequency
- Z_{ll}/n = 1.6 (MI longitudinal impedance per harmonic [5, 6])
- Single bunch intensity = 6×10^{10}.

(See reference [7] for the theoretical basis.) Simulations are also carried out with Z_{ll}/n = 3.2, 4.8, 6.4, 8 and 24×10^{10} (total intensity for 4 bunches). The longitudinal emittance growth verse Z_{ll}/n is shown in Fig. 5. The space charge voltage ranges from 20 to 300 V during the 2.5 MHz acceleration and 3 to 8 kV during the 53 MHz acceleration.

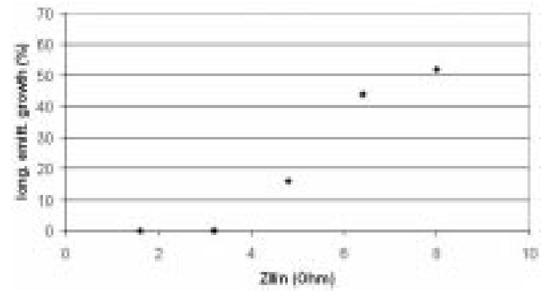

Figure 5: Longitudinal emittance growth vs. Z_{ll}/n.

Within a factor of three of Z_{ll}/n = 1.6, there is no significant emittance growth. For the case of bunch intensity 24×10^{10} and Z_{ll}/n = 1.6, the emittance growth is less than 5% and particle loss is less than 1%.

For the simulation with beam loading of the 2.5 MHz fundamental mode, four bunches and a single cavity are modeled in ESME. The quality factor and the shunt impedance of the 2.5 MHz cavity are 112.5 and 45000 Ω, respectively. To simulate the total beam loading voltage of five cavities, the shunt impedance is increased by a factor of five.

Simulations show that beam loading causes significant emittance dilution and phase shift to the bunch distribution. The peak beam loading voltage for the entire cycle and an instantaneous beam loading voltage are shown in Fig. 6. The maximum beam loading voltage furing the cy-

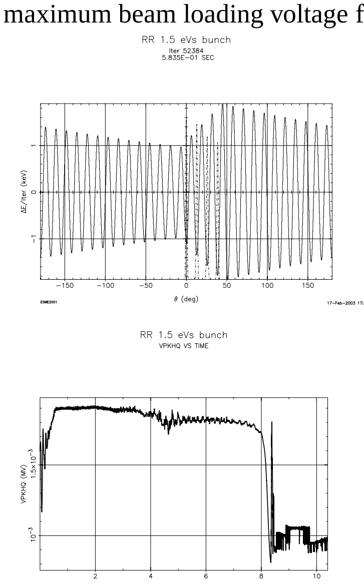

Figure 6: Top plot: Instantaneous beam loading voltage at a particular time along the ring. Bottom plot: Peak beam loading voltage during the entire cycle. Ignore voltage after 8.2 second at which 53 MHz acceleration takes over.

cle is about 1.9 kV. Beam loading problem is most severe at the beginning of the rotation at 27 GeV where the beam loading voltage is 1.4 kV and the cavity voltage is 3 to 4 kV. The bunches are shifted from their bucket centers by about 45 to 50 degrees. Large emittance growth (over a factor of 2) and significant particle loss are observed after the 53 MHz capture. In conclusion, beam loading compensation is needed for the 2.5 MHz acceleration scheme.

3 EXPERIMENTAL TEST OF 2.5 MHZ ACCELERATION IN MI

Preliminary test of the 2.5 MHz acceleration scheme is conducted using proton beam from the Fermilab Booster. As a first experiment, the Booster beam is used to produce 2.5 MHz bunches in the Main Injector and the bunches are accelerated from 8 GeV to 27 GeV. Since the 2.5 MHz radial and phase control systems are currently under development, the experiment is carried out with open loop conditions–no active radial feedback and phase feedforward controls.

Figure 7 represents a typical data sample taken during the proton acceleration. Four Booster batches are injected

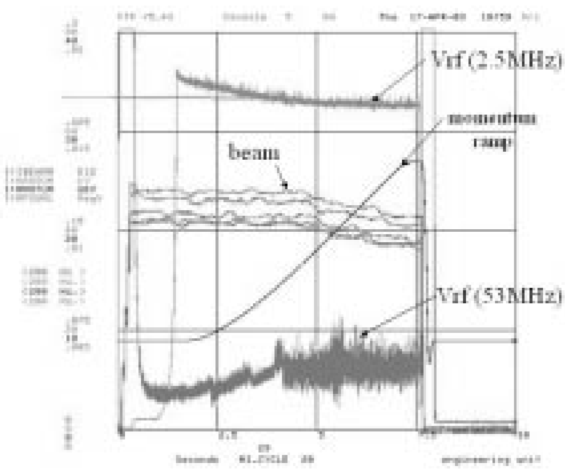

Figure 7: Beam–MI beam intensity in units of E12, Vrf (2.5 MHz)-rf voltage on 2.5 MHz rf system (kV), momentum (GeV), Vrf (53 MHz)-rf voltage on 53 MHz rf system (MV) as a function of time (sec).

into the Main Injector in succession and then are adiabatically debunched into four 2.5 MHz buckets. Once the beams are captured in 2.5 MHz buckets, the 2.5 MHz voltage is adiabatically raised to accelerate the beam. In the meantime, the 53 MHz voltage is paraphrased below 10 kV to minimize the 53 MHz component of the beam. There is 100% transmission up to transition (around 5.2 second). After transition, about 12% of the beam is lost. Since transition crossing is performed manually by moving (realigning) the 2.5 MHz buckets, transition loss is expected. In normal operation, transition phase jump will be controlled by the LLRF phase control system.

Figure 8 shows a sample of mountain range data for the early part of the cycle. The bunches exhibit oscillations and beam loss which are presumably due to the lack of radial and phase controls. These effects can also be due to the fact that the beam loading compensation systems are not yet effectively applied during the acceleration.

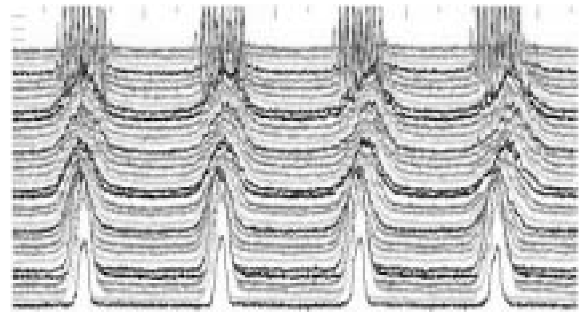

Figure 8: Mountain range bunch data. Four Booster batches of 7 bunches each are adiabatically debunched into four 2.5 MHz buckets. The 2.5 MHz bunches are subsequently accelerated to 27 GeV.

During the acceleration, the transverse emittance was measured using the MI flying wires. Data shows that there are no emittance growths in the transverse directions.

In summary, we have demonstrated 2.5 MHz acceleration up to 27 GeV with open loop operation as a proof of principle. The experimental results are consistent with our longitudinal beam dynamics simulations. In the future, with the operation of the radial and phase control systems, the issues of longitudinal emittance growth, beam loss and beam loading will be carefully examined.

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