BEAM INTENSITY LIMITS IN THE MAIN INJECTOR THROUGH TRANSITION WITH A NORMAL PHASE JUMP SCHEME

C. M. Bhat and J. A. MacLachlan
Fermi National Accelerator Laboratory*, P.O. Box 500, Batavia, IL 60510

Abstract

The Fermilab Main Injector, which is under construction, will be a high intensity proton synchrotron and will be capable of accelerating (decelerating) protons and antiprotons from 8.9 GeV/c to 150 GeV/c (150 GeV/c to 8.9 GeV/c). Presently, the plan is to accelerate or decelerate the beam through the transition energy of 20.49 GeV, using basic normal phase jump scheme. Efficient deceleration of $\bar{\mathrm{p}}$ through the Main Injector is crucial for the success of the Recycler Ring Project. We have performed extensive longitudinal beam dynamics simulations for both modes of operation to determine the beam intensity limits and other properties. We present the latest results of calculation and their implications.

1 INTRODUCTION

Upgrading the proton beam intensity in the Main Injector (MI) is important for the high energy $\mathrm{p\bar{p}}$ collider physics programs at the Fermilab Tevatron and for several proposed fixed target experiments using the Main Injector beam. Recently, it has been shown that with "slip stacking" [1] the proton beam intensity in the Main Injector at 8 GeV can be increased by a factor of two (or more) over the design bunch intensity [2] of 6×10^{10} particles per bunch (ppb). During the slip stacking, two batches of 84 proton bunches from the 8 GeV Fermilab Booster will be injected into the Main Injector with a small momentum offset; then they are brought together by rf coalescing. Finally, these high intensity bunches will be accelerated from 8 GeV to 120 GeV or 150 GeV through the transition energy of 20.49 GeV. Though the expected bunch area of the beam from the Booster is as small as 0.1 eV-sec [3], after slip stacking the final emittance will be in the range of 0.2-0.35 eV-sec. Passing transition with normal phase jump scheme at high longitudinal space charge density generally poses many problems. In this paper we have made an attempt to investigate any problem associated with acceleration of high intensity bunches through transition without changing the base line lattice of the Main Injector.

The Main Injector has four basic types of acceleration cycles, viz., $\bar{\mathrm{p}}$ production, MI Fixed Target slow spill and fast spill and, Tevatron collider. In the first three modes of operations the beam will be accelerated up to 120 GeV and in the collider mode the beam will be accelerated up to 150 GeV. In all these cases, the rate of change of momentum at transition is fixed (see Table 1) and and the maximum number of protons per bunch is expected to be about 15×10^{10}. Hence, one may encounter the general problems of transition crossing in all these cases.

Another issue addressed here is the deceleration of $\bar{\mathrm{p}}$'s from 150 GeV to 8 GeV. We plan to recycle the unused $\bar{\mathrm{p}}$'s at the end of each collider runs of the Tevatron. The $\bar{\mathrm{p}}$'s will be decelerated from 1 TeV to 150 GeV and injected into the Main Injector. The longitudinal bunch area of the beam at 150 GeV is expected to be about 3 eV sec and the $\bar{\mathrm{p}}$ intensity per bunch will be 7×10^{10}. This beam will be further decelerated to 8 GeV to store in a Recycler Ring which is being built in the MI tunnel [4].

Here we have performed longitudinal beam dynamics simulations using ESME [5] for both acceleration of high intensity bunches and deceleration of large emittance bunches by including space charge force and realistic beam pipe impedance. In this report we present some of the important findings of our studies.

2 ACCELERATION OF HIGH INTENSITY BUNCHES IN MAIN INJECTOR

It is known that the acceleration of bunches of charged particles across transition energy in a proton synchrotron needs special precautions [6]. In the baseline design of the Main Injector we plan to use only the rf phase jump scheme, i.e., switching the rf phase from ϕ to $\pi - \phi$ as the beam is accelerated through transition energy. Table 1 lists the design parameters of the Main Injector. Since the dp/dt at transition is about 250 GeV/c per second the non-adiabatic time is only about 2.1 msec. Hence the bunches are not very prone to emittance dilution. Because in addition there is approximately 1.5% momentum aperture, one might be able to accelerate the high intensity bunches across transition without any beam loss or significant dilution in the beam area.

Sudden change in rf phase along with the space-charge force of the particles in a bunch induce bunch oscillation at transition. These oscillations are known to be the one of the causes for emittance growth after transition. However, in the Main Injector a quadrupole oscillation damper like the one used in the present Main Ring will be installed to reduce bunch oscillations induced by transition crossing. This damper will be activated about 20 msec after transition crossing. Hence to identify any problems associated with transition crossing it is sufficient to perform simulations for about 100 msec around transition energy. In our simulation this quadrupole damper is not included.

The parameters of the Main Injector relevant to the simulations performed here are listed in Table 1. During transition crossing the space charge force and beam pipe

* Operated by Universities Research Association, Inc. under contract No. DE-AC02-76CH03000 with the U. S. Department of Energy

impedance play significant role. To reduce the beam pipe impedance special designs were developed to shield vacuum pump connections, bellows and any undesirable steps in the ring. Plans have also been made to reduce the impedance arising due to special structures of Lambertson magnets at extraction and injection regions. A conservative estimate of the $Z_{||}/n = 1.6\ \Omega$ [3]. However for simulation, we take $Z_{||}/n = 3\ \Omega$ which gives some safety margin.

Table I. The Main Injector parameters.

Mean radius of FMI	528.3019 m
γ_t (nominal)	21.838
$\dot{\gamma_t}$	267 sec^{-1}
α_1^a	0.002091
Maximum RF Frequency and RF Voltage	4 MV for 53 MHz 15 kV for 106 MHz 60 kV for 2.5 MHz 15 kV for 5 MHz
Protons ϵ_l at 8 GeV Injection I_{Bunch} at 8 GeV	 0.1–0.35 eVs 6–15 $\times 10^{10}$
Anti-protons ϵ_l at 150 GeV Injection I_{Bunch} at 150 GeV	 3–4 eVs 5–7 $\times 10^{10}$
Coup. imp. $Z_{\|\|}$/n	3 Ω
Beam pipe wave guide	1.5–2.2 GHz cutoff
cutoff frequency Transverse Beam size(a)	 2.2 – 5 mm
Beam pipe Radius (b)	5.8 cm (m)

[a] α_1 is the second order term in the expansion of path length.

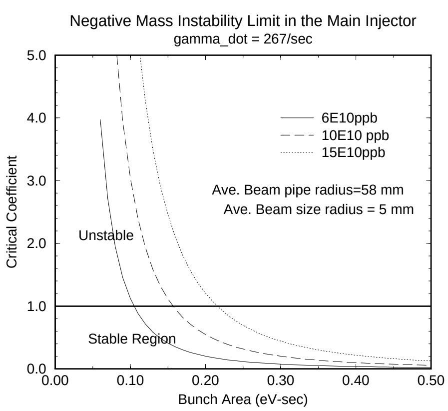

Figure 1: Negative mass instability limits [7] for beam intensity and emittance in the Main Injector. All ESME simulation results presented here pertain to beam properties corresponding to the stable region.

ESME simulations have been carried out using 10^6 macro particles per bunch and ignoring the beam current components above 14 GHz. We avoid negative mass instability by observing the stability limits calculated by W. Hardt [7]. Figure 1 illustrates the negative mass instability limits for three beam intensities as a function of bunch area. The frequency range used in the ESME simulations does display the qualitative features of negative mass instability for low emittance beam.

Figure 2 shows phase space distribution for the highest beam intensity bunch discussed here. We find that the phase space density is almost unchanged across transition.

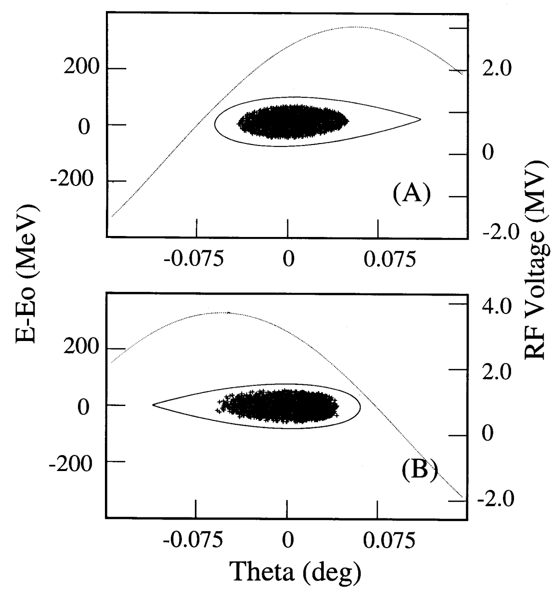

Figure 2: Phase space distribution (i.e., ΔE vs $\theta = \Delta\phi$) of 0.25 eV-sec proton bunch in an accelerating rf bucket in the Main Injector with 53 MHz rf system. The closed contours represent the buckets for the case at 20 msec (A) before (B) after transition. The rf wave form is also shown. The cases shown are for 15×10^{10} ppb.

From these simulations we found that with the normal phase jump scheme in the Main Injector the beam bunches with 15×10^{10} ppb and emittance 0.25 - .35 eV-sec can be accelerated through transition without any noticeable emittance growth and with no beam loss. If the beam longitudinal emittance is less than about 0.20 eV-sec then one might expect considerable emittance growth due to negative mass instability.

3 DECELERATION OF $\bar{\text{P}}$ BEAMS

For deceleration of $\bar{\text{p}}$, we have investigated two different types of accelerator cycle. In the first method the 3 eV-s beam bunch is captured at 150 GeV using 53 MHz rf buckets (h = 588, V_{rf} = 0.5 MV). Then the bunch is rotated with a 2.5 MHz system (h = 28, V_{rf} = 35 kV) and is matched. The typical matching voltage was about 400 V. Then the bunch is divided in to several bunches by raising the h = 588 rf voltage adiabatically. This takes less than 300 ms at 150 GeV. Thus a 3 eV-s beam bunch is distributed among 11 to 13 bunches. Finally this train of bunches is decelerated to 8 GeV in less than 2 sec. In this process we noticed about a factor of 2 emittance growth and up to about 5% beam loss at transition mainly arising from to non-linear effects on the larger central bunches.

In the second method, the transferred bunch of $\bar{\text{p}}$ from Tevatron is decelerated from 150 GeV to 25 GeV in about 1.7 sec using h=588 system. On a "front porch" at 25 GeV, about 1.8 sec, the $\bar{\text{p}}$ bunch is transferred to a h=28 bucket with V_{rf}=60 kV and is rotated. At the end of bunch rotation the rf voltage is set to match the beam (i.e., lowered to $\leq$300 V) and raised adiabatically to shrink the bunch. An overall 10% emittance growth is observed during the bunch rotation and shrinking. This bunch is further decelerated using h=28 system. Since the V_{rf}(max) for the h=28 system is limited to 60 kV, the deceleration from 25 GeV to 8 GeV is performed rather slowly. In the scheme proposed here this part of the deceleration is performed in two steps. The deceleration from 25 GeV to 15 GeV with dp/dt $\approx$ -2.5 GeV/c-sec; the later part is carried out with dp/dt$\approx$ -1.4 GeV/c-sec. Thus the entire deceleration process for four bunches of $\bar{\text{p}}$'s takes about 12.5 sec. We find no beam loss and the maximum emittance growth is about 9%.

Figures 3 shows the ramp curve for the second method. Various types of rf manipulations performed during deceleration are indicated. Figure 4 shows the phase space distribution from ESME simulation for a decelerating $\bar{\text{p}}$ bunch with initial longitudinal beam emittance 3 eV-s and with 7×10^{10} $\bar{\text{p}}$pb. We find that the phase space density is almost unchanged across transition.

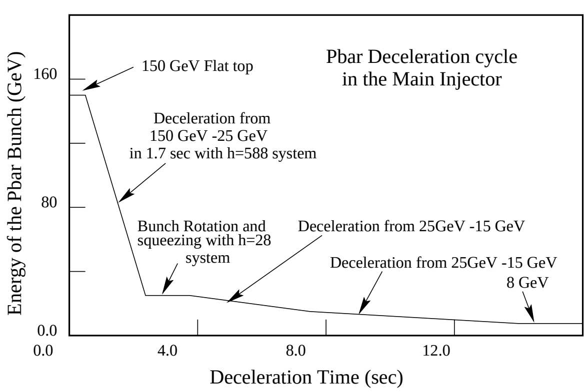

Figure 3: A 12.5 sec long $\bar{\text{p}}$ Deceleration cycle used for simulation.

The second method for deceleration has some disadvantages, though the quality of the beam is maintained through out the process. The disadvantages are that since the entire process takes rather long, it might result in an unacceptably long time to decelerate all 36 (or 99) $\bar{\text{p}}$ bunches from the Tevatron. Also there is some concern about the stability of the Main Injector magnetic field quality if the magnet current is varied very slowly. However, we are convinced that the longer deceleration time at low magnet current should not pose a problem operationally. For the first method the deceleration the time involved is small; hence is still a good choice.

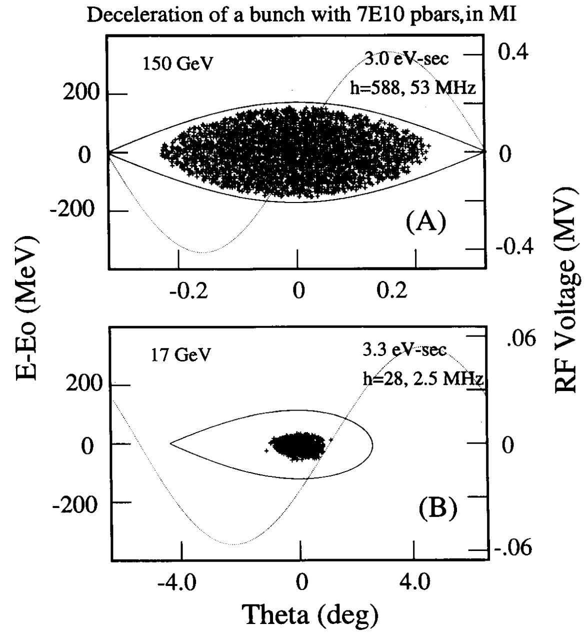

Figure 4: (ΔE vs $\Delta\phi$) distribution of the particles in a decelerating bucket of Main Injector. A) 53 MHz rf system at 150 GeV, B) 2.5 MHz rf system at 17 GeV. For other details see caption of Fig. 3.

4 SUMMARY

We have performed multi-particle beam dynamics simulations for both acceleration and deceleration of beam In the Main Injector. We find that bunches with 15×10^{10} protons and with longitudinal emittance of 0.25 eV-s can be accelerated through transition with out any dilution. For deceleration we investigated two methods of operation, the choice between them will depend on the relative importance of cycle time and deceleration efficiency in an optimized recycling scenario.

5 REFERENCES

[1] S. Shukla, J. Marriner and J. Griffin (Private communication m 1997)

[2] The Fermilab Main Injector Technical Design Handbook (1994, updated 1997).

[3] Run II Design Hand Book (1995).

[4] "Fermilab Recycler Ring Technical Design Report",edited by G. Jackson, FERMILAB-TM-1981

[5] J. MacLachlan, Computer code ESME.

[6] A. Sorenssen, Part. Accelerators, Vol. 6, 114 1975.)

[7] W. Hardt *et al., Proceedings of the 8th International Conference on High Energy Accelerators*, (Geneva, 1971) p. 323.