MOMENTUM SPREAD REDUCTION AT BEAM EXTRACTION FROM THE FERMILAB BOOSTER AT SLIPSTACKING INJECTION TO THE MAIN INJECTOR*

X. Yang†, A.I. Drozhdin, W. Pellico, FNAL, Batavia, IL 60510, USA

Abstract

In order to reduce the momentum spread of the beam at extraction from the Booster to the Main Injector with slip stacking injection, the bunch rotation at the end of the cycle is applied. However, the fast RF voltage reduction often causes beam loading issues to Booster RF cavities, and the reliability of extracted beam becomes a problem. An alternative solution is investigated - modulating the RF voltage with twice of the synchrotron frequency introduces bunch length oscillation, and the beam is extracted at the time when the bunch length reaches maximum and the momentum spread becomes minimal.

INTRODUCTION

In order to achieve the antiproton production rate of 2.4e11 per hour, it requires the Booster to be able to deliver 8 GeV proton beams to the Main Injector at the intensity of 4.5e12 ppp with a momentum spread of $8\ MeV$ and a longitudinal emittance of 0.1 $eV \cdot s$. The requirements on beam parameters at extraction are set by the Booster bunch match to the Main Injector bucket at slip stacking injection. The longitudinal phase planes for the first (top) and second (bottom) beam at slip-stacking injection to the Main Injector are shown at Fig. 1. First three particles of the first beam and last three particles of the second beam with momentum offset $dP \geq 8.5\ MeV$ are lost from separatrix because of beams acceleration/deacceleration at injection. The longitudinal size of a stable beam is $\sim \pm 2.0$ radian. These parameters ($dP \leq 8\ MeV$ and $d\varphi =\sim \pm 2.0$ radian) were used for beam extraction optimization in the Booster.

The momentum spread of a nominal 8 GeV Booster beam at this intensity is about 15 MeV. The required reduction of the bucket height can be achieved using the bunch rotation via RF voltage reduction at the end of the cycle before beam extraction to the Main Injector. However, the fast rf voltage reduction frequently causes beam loading issues to rf stations, and reliabilities of extracted beams become a problem.

An alternative solution has been numerically investigated using 3-D STRUCT [1] code. Modulating the rf voltage at the end of a cycle at twice the synchrotron frequency introduces bunch length oscillation. Afterwards, the 8 GeV beam is extracted at the time when the bunch length reaches the maximum and the momentum spread reaches the minimum.

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† xyang@fnal.gov

NUMERICAL INVESTIGATION

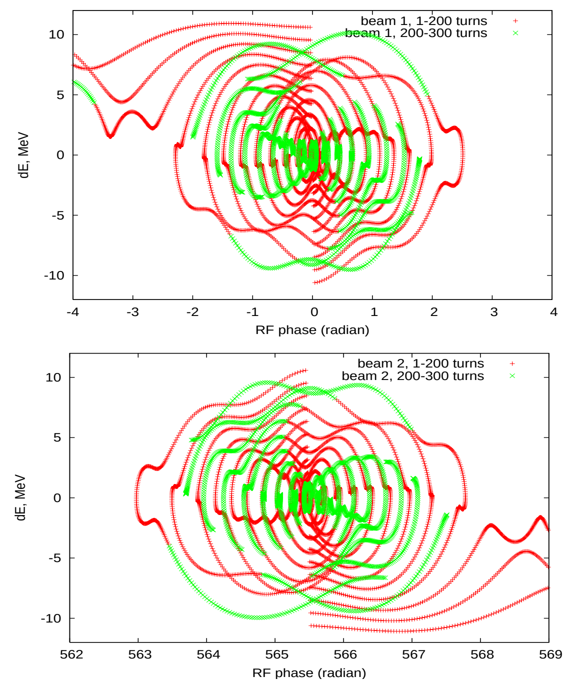

Figure 1: Longitudinal phase plane for the first (top) and second (bottom) beam during first 300 turns after slip-stacking injection to the Main Injector.

There are three parameters: the initial voltage, the modulation amplitude, and the number of bunch length oscillations right before the extraction, to be adjusted in order to optimize the momentum reduction process in the Booster. Usually, the lower the initial voltage is, the smaller the minimum momentum spread can be achieved. However, if the initial voltage is small enough to make large amplitude particles close to the bucket boundary, the nonlinearities will cause the longitudinal emittance growth. Also, a large number of oscillations will cause the nonlinearity problem, so a reasonable number of oscillations before extraction should be in the range of 2-4.

We usually start with a fixed initial rf voltage, which depends upon the beam intensity, and vary the modulation amplitude. At each momentum spread minimum, the longitudinal phase space is examined in order to avoid the nonlinearity problem. Afterwards, these calculations are repeated at different initial rf voltages for the final optimization.

Including space charge effect and radial feedback control system in our simulations, the initial rf voltage is fixed to $0.4\ MV$, and the modulation depth is varied at the optimization. Four different amplitude modulations, 15% (red), 25% (green), 35% (blue), and 45% (magenta) are used. rf voltage, synchronous phase, and momentum spread $dP_{95\%}$ are shown in Fig. 2. Longitudinal phase space is plotted in Fig. 3 at the first four momentum spread minimums when the modulation amplitude is 25%.

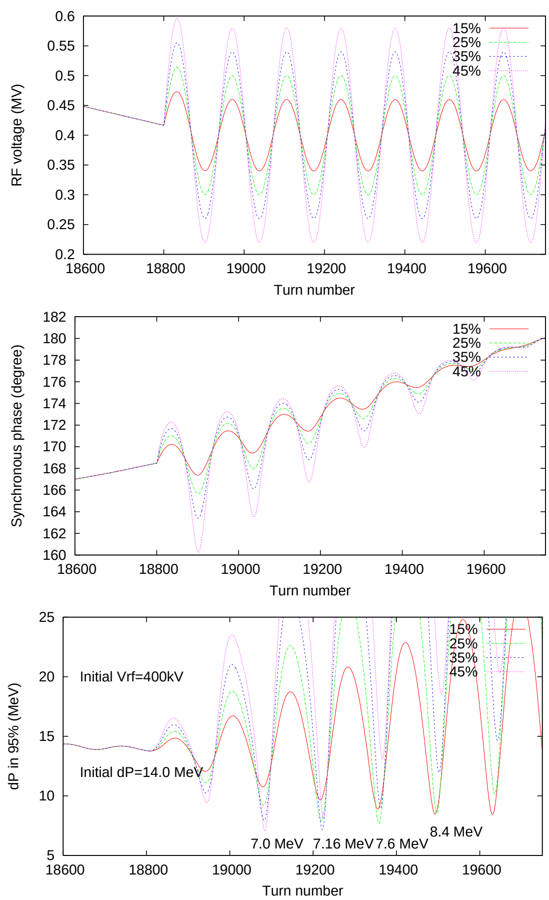

Figure 2: rf voltage (top), synchronous phase (middle), and $\Delta P_{95\%}$ at operational rf voltage of 0.4 MV for four different amplitude modulations, 15% (red), 25% (green), 35% (blue), and 45% (magenta).

The best result is found at voltage of $0.2\ MV$ and modulation amplitude of 35%. An optimal extraction time corresponds to the 2-nd minimum of momentum spread oscillations. Nevertheless, in the calculations the bunch was injected to the Main Injector at three different conditions: right before oscillations (blue), at the $1-st$ (green) and the 2-nd (red) momentum spread minimum with the injection momentum correction in the Main Injector for each case according to the extracted beam momentum in the Booster, as show in Fig. 4. The beam tracking in Main Injector shows losses of 15%, 8.4%, and 5.4% for those three cases. As shown on the longitudinal phase plane at turn 200 after slip-stacking injection to Main Injector presented in Fig. 5 for these three cases, the least particles number escaping from the separatrix, compared to other two cases, is in the case of extraction at the 2-nd momentum spread minimum.

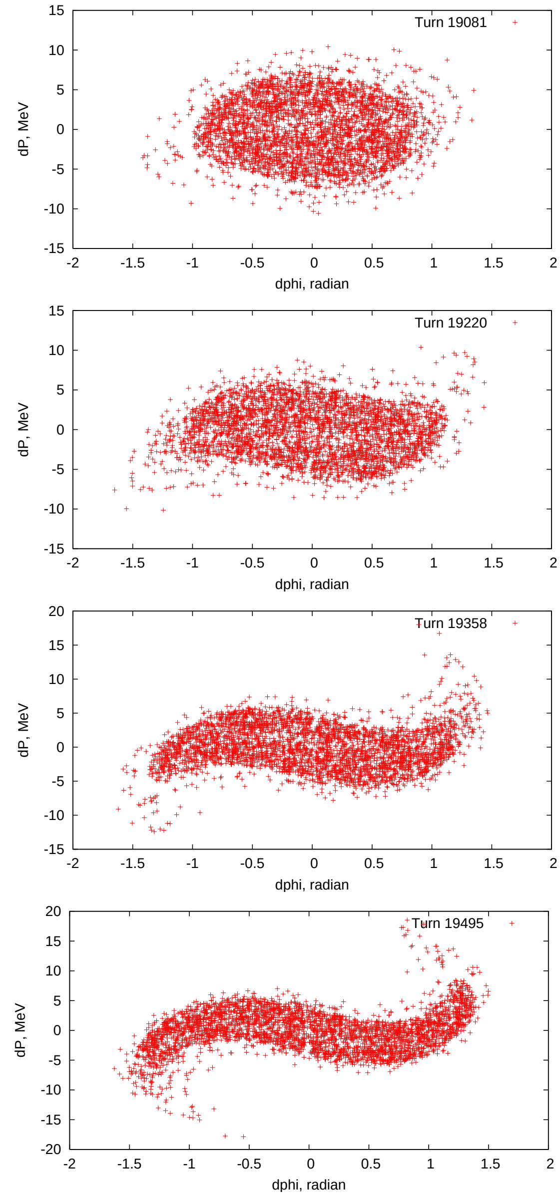

Figure 3: Longitudinal phase space at the first four momentum spread minimums for modulation amplitude of 25%.

The optimal condition is applied to the operation, as show in Fig. 6, to achieve $2-3\%$ loss reduction at slip stacking injection in the Main Injector.

CONCLUSIONS

It was shown that modulating the rf voltage at the end of the Booster cycle with twice the synchrotron frequency causes the bunch length and momentum spread oscillation. Extracting the beam at one of the momentum spread minimums allows to optimize extracted beam momentum spread and bunch length for matching to separatrix in the Main Injector at slip-stacking injection. The process have been investigated via varying the Booster rf voltage at extraction and the modulation amplitude. The effect of extraction conditions to beam loss in the Main Injector at slip-

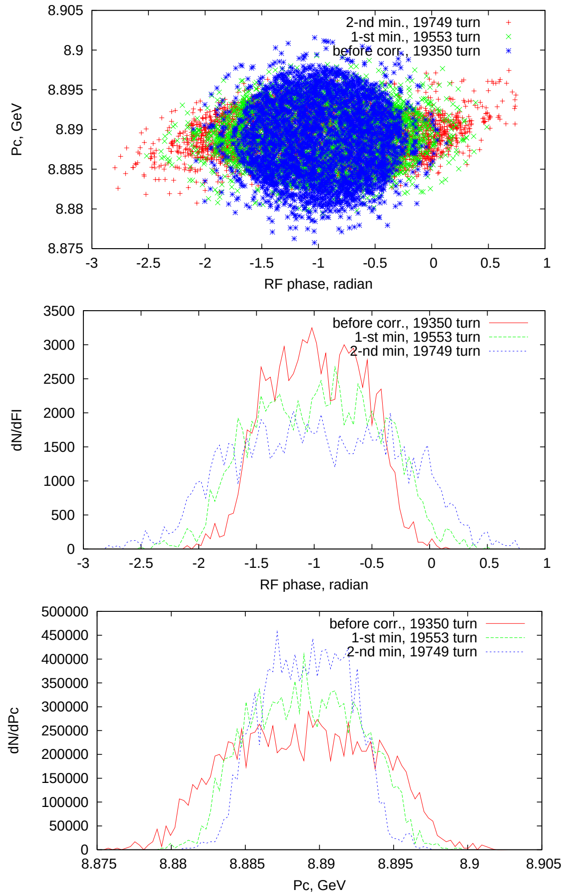

Figure 4: Longitudinal phase plane in the Main Injector (top) with injection momentum correction for different conditions of extraction from the Booster: right before momentum spread oscillation (blue), at $1-st$ minimum (green), and the 2-nd minimum (red). Middle - bunch length and bottom - momentum spread.

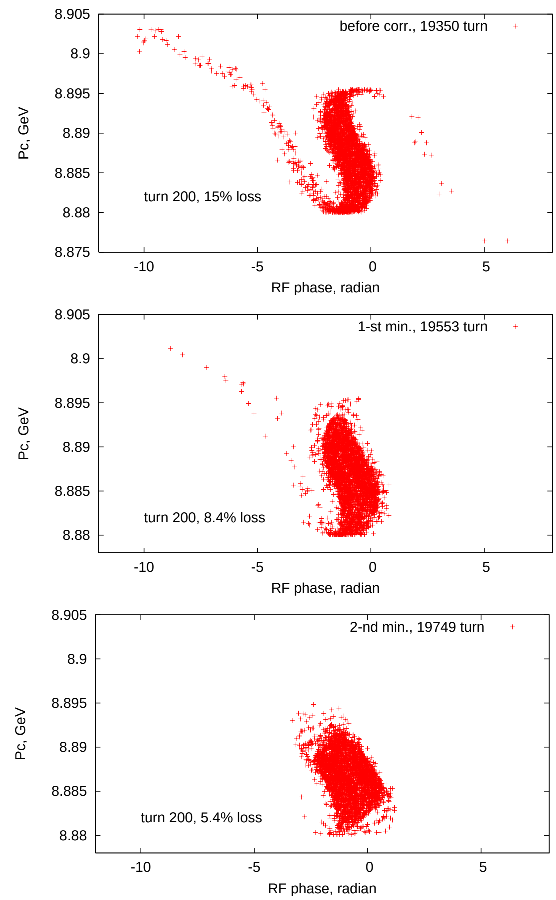

Figure 5: Longitudinal phase plane at turn 200 after injection to the Main Injector for extraction from the Booster right before momentum spread modulation (top), at the $1-st$ minimum (middle), and at the 2-nd minimum (bottom).

stacking injection have been numerically investigated. The optimized conditions have been applied to the Booster operation, and since then, the extracted beam quality has been improved with a much better consistency.

REFERENCES

[1] I. S. Baishev, A. I. Drozhdin, N. V. Mokhov, X. Yang "STRUCT Program User's Reference Manual", http://www-ap.fnal.gov/users/drozhdin/.

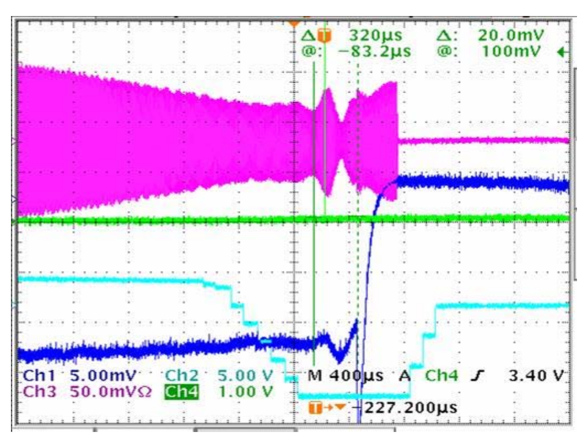

Figure 6: Voltage with amplitude modulation (magenta) and bunch length (blue) at the end of a cycle.

