INJECTION PARAMETERS OPTIMIZATION FOR THE FERMILAB BOOSTER*

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Abstract

The maximal capacitance for the Booster to deliver the 8-GeV beam to downstream accelerators is limited by the beam loss. Most of losses happen at injection due to space charge effect being the strongest at the injection energy. Optimizing the RF voltage ramp in the presence of the space charge effect to capture more beam and simultaneously keep small beam emittance has been numerically investigated using 3-D STRUCT [1] code. The results of simulations agree well with the measurements in the machine. Possibilities, such as beam painting and using the third RF harmonic at injection, for further reductions of beam loss in order to reach the maximum beam intensity delivered from Booster have been investigated.

RF VOLTAGE RAMP OPTIMIZATION

Table 1: Fermilab Booster injection parameters.

Beam kinetic energy, MeV	400.0
Bunch frequency, MHz	201.25
Linac RF frequency, MHz	805.0
Booster RF frequency, MHz	37.868
Booster repetition rate, Hz	15.0
Booster intensity, ppp	5.65e+12
Normalized transverse emittance, $\sigma_{x,y}$, mm-mrad	1.3
dp/p, σ	0.0001
Bunch length, 6σ, ns	0.78

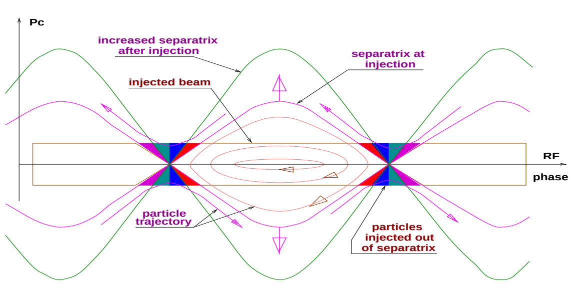

Figure 1: Longitudinal phase plane at injection with uniform distribution of injected beam on phase.

The $E_{kinetic} = 400\ MeV$ beam is injected from the linac during 14-turn foil stripping injection. Some amount of particles injected outside of separatrix in the vicinity of separatrix ends (Fig. 1) may be captured to acceleration at voltage gain after injection. This amount depends on the voltage ramp. Unfortunately voltage ramp effects bunch momentum spread growth and possible particle losses. Evolution of particle number in the RF bucket during 400 turns after injection (top) and particle loss at the accelerator aperture (middle and bottom) are shown in Fig. 2. The top of figure 2 indicates the amount of particles drifting away from the current bucket during first 25-30 turns after injection independently on the voltage ramp. Only small amount of particles is eventually lost at accelerator aperture, and most of them is recaptured by adjacent buckets. Beam losses continue up to 200 turns at low voltage ramp and disappear at the ramp of ~1.75 kV/turn. Particles escaped from separatrix during first 200 turns are lost later on the accelerator aperture at turns 200-400 (Fig. 3).

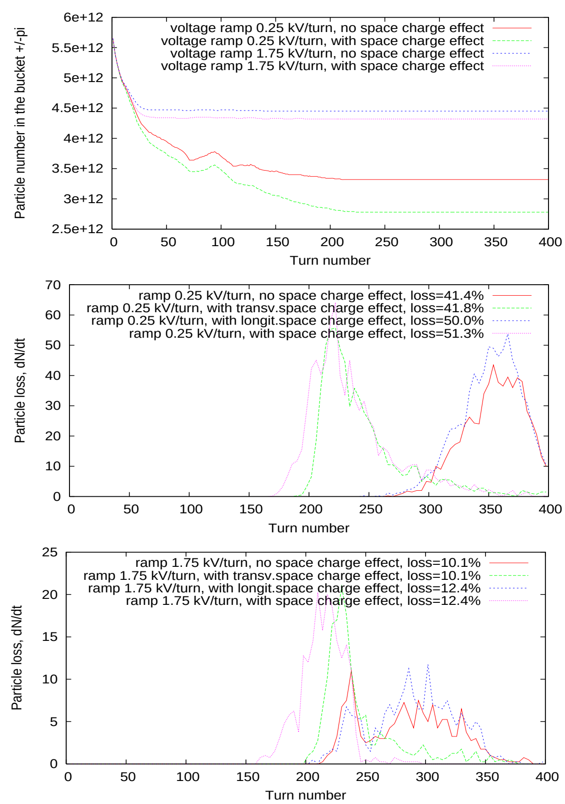

Figure 2: Particle number in the bucket as a function of turn number (top) and particle loss at the aperture (middle and bottom) for RF voltage ramp of 0.25 and 1.75 kV/turn.

SPACE CHARGE EFFECT SIMULATION

Actually the beam is injected from the linac by a short bunches ($T_{6\sigma} \simeq 0.8\ nsec$) with a distance of $\sim 5\ nsec$ between bunches, refered here as a "micro-bunch" injection. This makes a big difference in the space charge effect compared to the case shown at Fig. 1. Longitudinal phase plane of the beam at turn 100 after injection is shown at Fig. 4 for uniform distribution of injected beam without (top) and with (middle) space charge effect. The same distribution with space charge effect for micro-bunch injection is pre-

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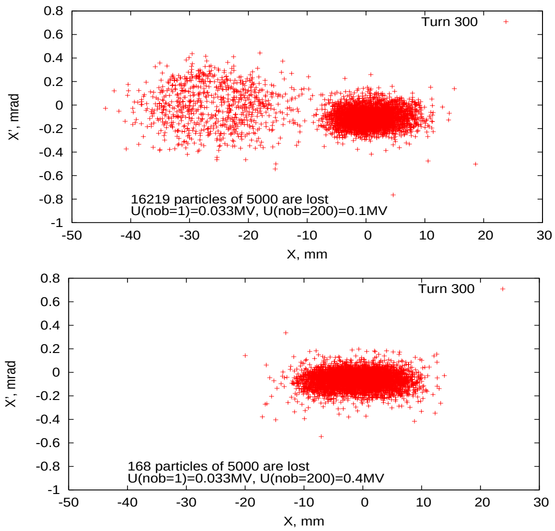

Figure 3: Transverse phase plane at turn 300 for RF voltage ramp at injection of 0.25 (top), and 1.75 kV/turn (bottom).

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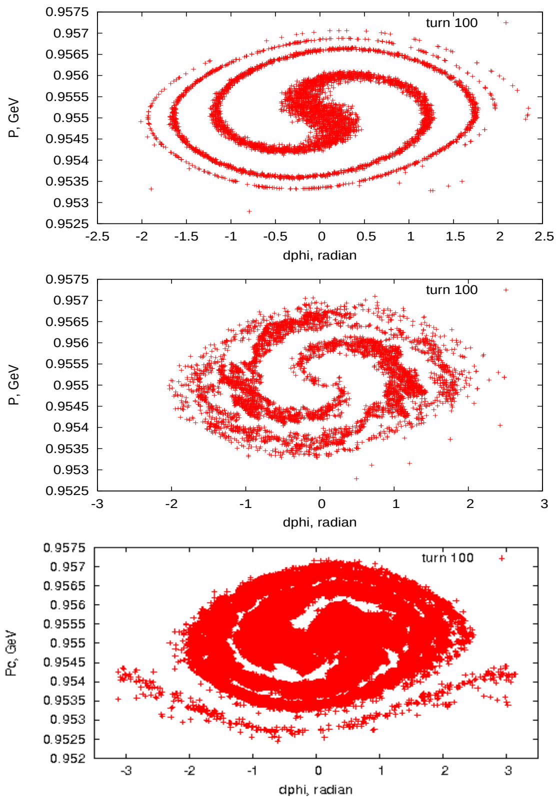

Figure 4: Longitudinal distributions of the circulating beam at turn 100 without (top), with (middle) space charge effect for uniform distribution of injected beam, and with (bottom) space charge effect for micro-bunch injection.

Longitudinal space charge effect is simulated by dividing the longitudinal beam profile into bins and calculating the beam current at these bins. Afterwards, a Fast Fourier Transformation (FFT) is done on the beam current, the voltage generated by the beam current due to longitudinal space charge impedance is calculated in the frequency domain. Finally, an inverse FFT is done on this voltage, and the real part is used to apply the momentum kick to macro-particle based upon the longitudinal bin position where the macro-particle is.

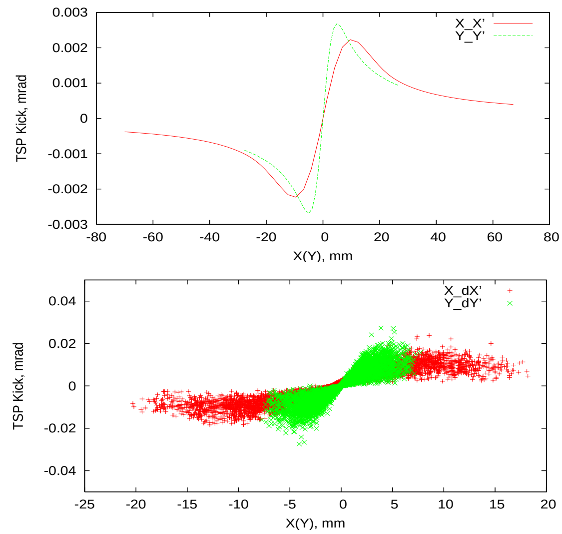

Figure 5: Transverse space charge effect calculated using complex error function.

Angular kick produced by transverse space charge forces is calculated from scalar potential using complex error function, assuming that the beam has a Gaussian distribution in X-Y plane. Transverse space charge kick at 1 m length of accelerator for the test particle which belongs to the horizontal or vertical axis is shown on the top of Fig. 5. The kick distribution for the total beam at length of 6.58 m is shown in the bottom.

As shown in Fig. 2 (bottom), the calculated beam losses (10.1%) are defined mostly by injected beam parameters and RF voltage at injection, the measured beam losses in the Booster (Fig. 9) are equal to $\sim 9\%$. The longitudinal space charge effects additional 2.3%. The transverse one does not increase amount of losses, but makes them faster moving the pick of losses from 300 to 200 turns for optimal voltage ramp.

The beam momentum spread increases fast during a quarter of synchrotron oscillation (15 turns) from $dp/p = 0.0003$ to 0.0030. As shown at Fig. 6 the beam has a spiral shape in a phase plane because of nonlinear dependence of synchrotron oscillation frequency on particle amplitude. Particle loss from separatrix due to space charge effect develop a visible fraction of particles on the lower side of separatrix on momentum at turn 100. This fraction miss acceleration as shown in the middle and bottom of Fig. 6 and is finally lost at turns 150-250.

Longitudinal (top) and momentum (bottom) distributions of the circulating beam at turns 1, 15, 60, 200 and 300 are shown at Fig. 7 for micro-bunch injection simulation with longitudinal and transverse space charge effect.

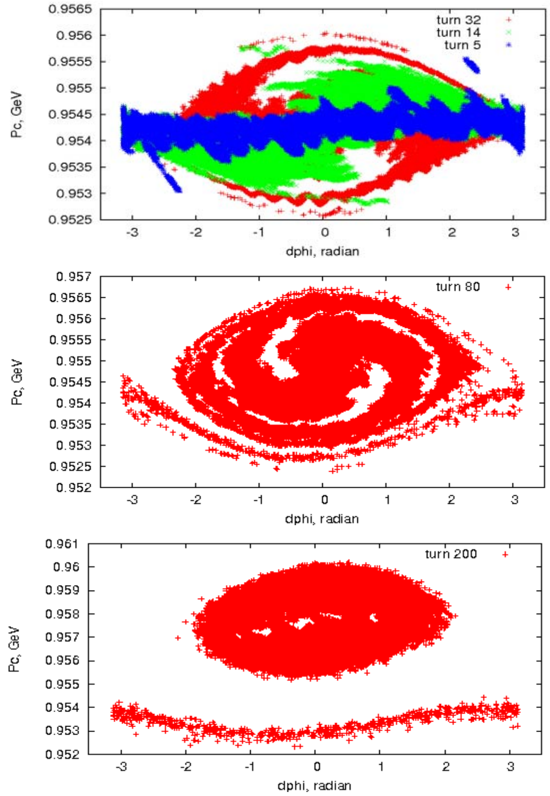

Figure 6: With micro-bunch injection simulation, transverse distributions of the circulating beam at turns 1-32 (top), at turn 80 (second line), and at turn 200 (bottom) with longitudinal and transverse space charge effect.

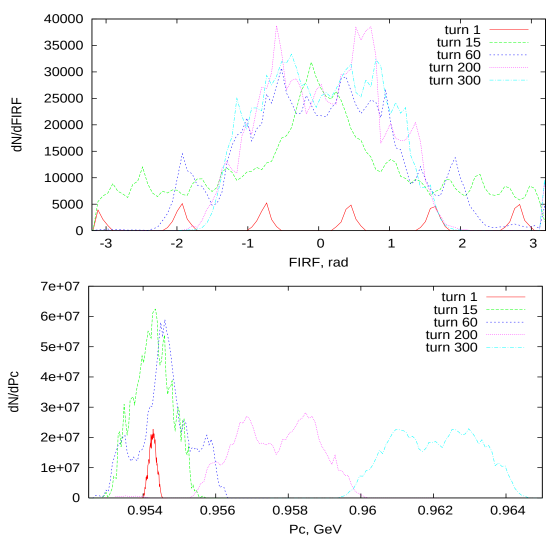

Figure 7: Beam parameters evolution at injection.

USE OF THIRD HARMONIC OF RF VOLTAGE FOR LOSS REDUCTION

At injection, the third harmonic of RF voltage provides the more square bucket shape without increasing the bucket height. It can simultaneously reduce an injection loss and momentum spread. The amount of injection loss reduction depends upon the beam intensity. The higher the beam intensity is, the larger the loss reduction is. The tracking of 10 test particles with initial phases from -3.14 to 3.14 at injection is presented at Fig. 8 for the cases with (red) and without (green) third harmonic. The ratio of third harmonic to fundamental one is ~ 1.2 in these cases.

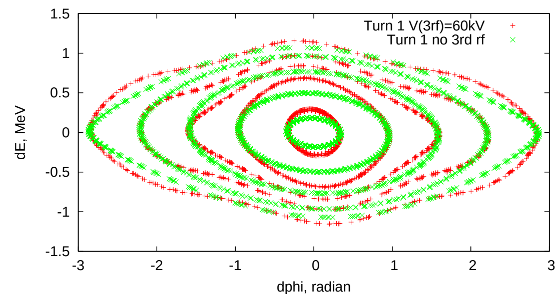

Figure 8: Longitudinal phase contours at injection.

CONCLUSIONS

Our calculations show that beam losses at injection depend drastically on the RF voltage gain, going down from $\sim 50\%$ at voltage ramp of 0.25 kV/turn to $\sim 12\%$ at ramp of 1.75 kV/turn. Booster measured efficiency ($\sim 88\%$), including the beam notch is shown in Fig. 9 by red and green colors. The beam notch is a gap, created for extraction by kicking out of three bunches at injection. Excluding the beam notch, the efficiency should be equal to $\sim 91\%$.

The beam momentum spread grows from $dp/p = 0.0003$ to 0.0030 during 15 turns after injection due to nonlinear phase rotation in the separatrix. The final spread depends on the RF voltage applied.

At optimal voltage ramp the longitudinal space charge effects additional $\sim 2\%$ losses at injection. The transverse one does not increase amount of losses, but makes them faster moving the pick of losses from 300 to 200 turns for optimal voltage ramp.

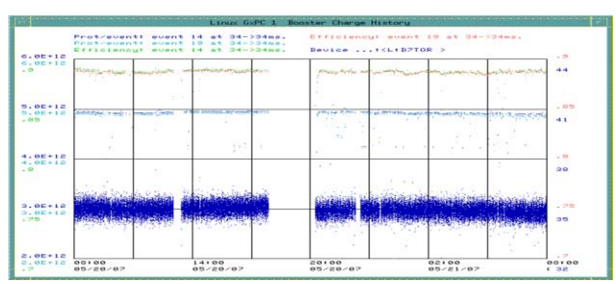

Figure 9: Linac intensity (bottom, blue), Booster injected intensity (top, blue) and Booster efficiency (green) during a day of operation.

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/.

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