

TRANSITION CROSSING SIMULATION AT THE FERMILAB BOOSTER*

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Abstract

The demand in high intensity and low emittance of the beam extracted from the Booster requires a better control over the momentum spread growth and bunch length shortening at transition crossing, in order to prevent beam loss and coupled bunch instability. Since the transition crossing involves both longitudinal and transverse dynamics, the recently modified 3-D STRUCT [1] code provides an opportunity to numerically investigate the different transition crossing schemes in the machine environment, and apply the results of simulation to minimize the beam loss and emittance growth operationally.

CHROMATIC EFFECT AT TRANSITION CROSSING

The nonlinear chromatic effect may cause emittance growth during transition because the particles with different energies cross transition at different times. If the phase jump at transition is set for synchronous particle, then at a cycle time below transition, the particles with positive energies with respect to synchronous one are unstable, and particles with negative energies are unstable at cycle time above transition. Based upon MAD calculations, the dependence of transition energy upon the momentum deviation can be adjusted by sextupole corrector settings. As shown in Fig. 1, this dependence in the Booster can be removed at corrector setting of $I_{sextl}=-97A$ and $I_{sexts}=97A$. The dependence of transition energy upon the momentum deviation was measured experimentally. For this purpose the beam losses were measured at transition crossing as a function of transition time for two radial positions of the beam: $1.31mm$ and $-0.74mm$, and the optimal transition time was determined for both cases. The difference in transition energies ($\delta\gamma_t$) for these two cases calculated from the accelerating ramp is 0.0066 , as shown in Fig. 2. It agrees with the MAD calculation of $\delta\gamma_t=0.00726$, within 10%.

MISMATCH AT TRANSITION CROSSING

The transition crossing is space charge dominated in the Booster. Since the longitudinal space charge forces are always repulsive, they counteract the rf focusing below transition and enhance focusing above transition. According to simulations, right above transition crossing (turn ~ 9480 at the top of Fig. 3), the bunch will appear with the larger length left over from the influence of the space charge forces below transition, and the equilibrium bunch length

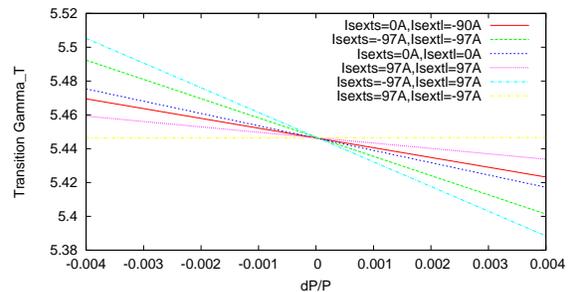


Figure 1: Transition energy dependence in the Booster upon momentum deviation calculated using MAD for different sextupole corrector settings.

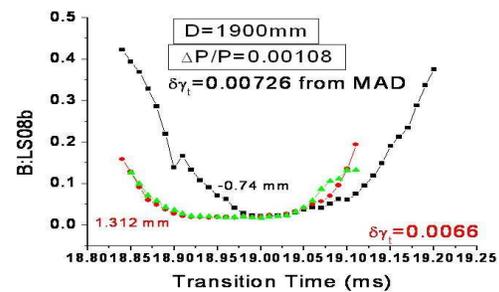


Figure 2: The beam loss at transition for two radial positions of the beam: $1.31mm$ (red and green) and $-0.74mm$ (black).

is now even shorter than that without space charge. The bunch length starts to oscillate above the transition energy because of such a mismatch. Above transition, the nonlinear dependence on amplitude of the particle motion along the phase trajectories effects filamentation and dilution of the longitudinal emittance. The results of simulation and experimental observation, as shown in Fig. 3, are agree quite well with each other.

VOLTAGE JUMP USING 3-RD HARMONIC OF RF VOLTAGE

Voltage jump scheme was proposed by Valeri Lebedev [2] to compensate the space charge induced mismatch by increasing the rf focusing right below transition. However, at least a 300 kV increase in a fundamental rf voltage is required for the beam intensity of $\sim 4.5e12$ ppp [3], what is difficult to get from the present rf system. Nevertheless, if one uses the 3-rd harmonic of rf voltage, the only one third of the fundamental rf voltage is needed for the same amount of the rf voltage slope increase. Also, since the bunch is so short at transition, the phase jitter of the 3-rd

* Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH03000 with the U. S. Department of Energy.

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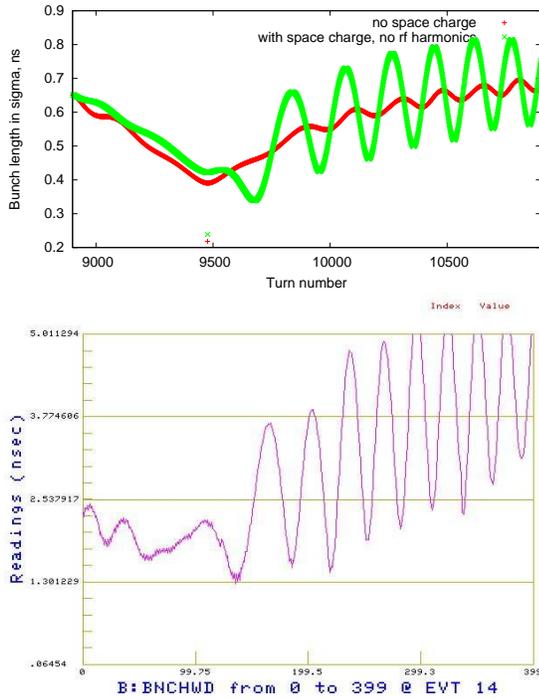


Figure 3: The σ of bunch length vs turn number in simulations at the beam intensity of $5e12$ ppp, without (red) and with (green) space charge effect (top), and measured in the Booster 4σ of bunch length (bottom).

harmonic with respect to the fundamental one could be up to $10^\circ - 20^\circ$, and this can be easily achieved by the present Low Level RF control system.

The simulation has been done for two cases of 3-rd harmonic rf voltage: the ideal case with 120 kV and the realistic case with 60 kV [4]. In an ideal case, the only one voltage pulse is needed right before transition to largely remove the space charge induced mismatch at transition; in the 60 kV case, not only a longer pulse is needed before transition, but two more short pulses are required after transition to remove the residual mismatch. The bunch length and 3-rd harmonic voltage are shown in Fig. 4 for the ideal case (red), the realistic case (green), and transition crossing without voltage jump (blue).

RADIAL MOTION FOR MISMATCH COMPENSATION

The voltage jump scheme requires an upgrade of the existing rf system. And before this happens, we may take advantage of application of radial motion to compensate the space charge mismatch. Radial motion can be achieved by decelerating or accelerating the beam relative to the equilibrium energy. When the beam instantaneously lose energy with respect to equilibrium one, it moves radially inside, and vice versa. Right below transition, the synchronous phase is in the range of $0^\circ - 90^\circ$. By decelerating the beam relative to equilibrium energy, using synchronous phase decrease, will effect more rf focusing to compensate

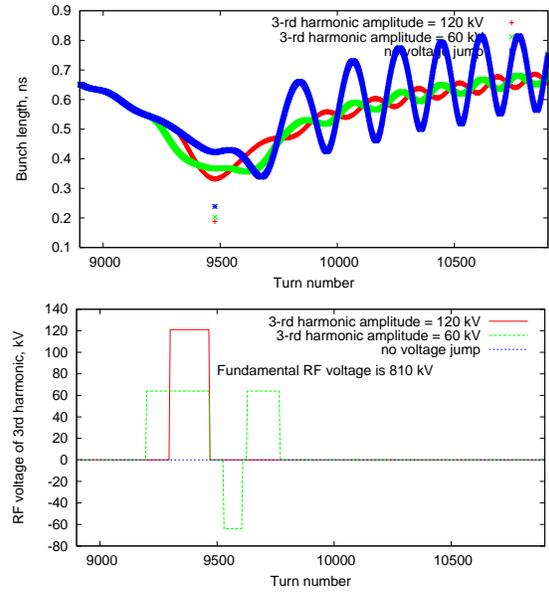


Figure 4: Bunch length (top) and 3-rd harmonic of rf voltage (bottom) at the Booster intensity of $5e12$ ppp for three cases: voltage jump with 3-rd harmonic amplitude of 120 kV (red), with 3-rd harmonic amplitude of 60 kV (green) and without voltage jump (blue).

the space charge defocusing.

Right above transition, the synchronous phase is in the range of $90^\circ - 180^\circ$. An acceleration of the beam relative to equilibrium energy can be done by decreasing the synchronous phase, what also will effect the rf defocusing to compensate the space charge focusing.

So the radial motion for the space charge compensation at transition crossing should be radially inside of the ring right below transition and outside of the ring right above transition. How much the space charge induced mismatch at transition can be compensated by radial motion depends upon the available aperture. At the beam intensity of $4.5e12$ ppp, the radial motion shown in Fig. 5 is experimentally optimized to reduce the beam loss at transition. The residual mismatch induced by the space charge effect could be removed by the quad damper.

The available aperture for a beam gymnastics is about 12 - 14 mm at the beam intensity of $4.5e12$ ppp, and it is used in the simulation. The radial motion is optimized for the compensation of space charge induced mismatch. Since the residual mismatch above transition is normally removed by the quad damper, the more mismatch will be removed by radial motion, the less quad damper voltage is required. This also is better for the Booster rf stations. The results of simulation, including voltage feedback from quad damper, are shown in Fig. 6. After the optimized radial motion is implemented in the operation, the amplitude of bunch length oscillations above transition is reduced by $\sim 50\%$, as shown in Fig. 7 compared to Fig. 3.

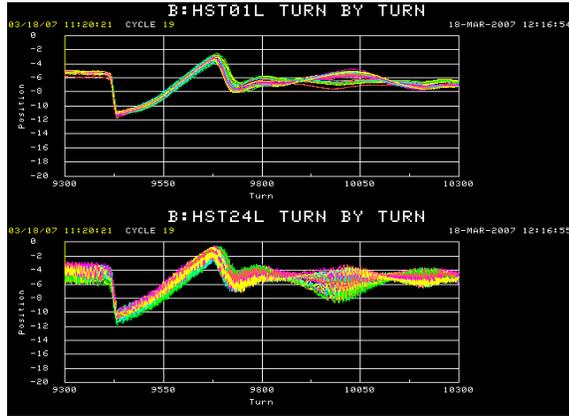


Figure 5: Turn by turn data, taken from the beam position monitor at transition period for the beam intensity of $5e12$ ppp.

CONCLUSIONS

The chromatic non-linear effect has much less influence on the transition crossing compared to the space charge effect. We wish to remove the source of emittance growth instead of relying upon the quad damper after transition. Before the 3-rd harmonic *rf* cavity is built for the voltage jump scheme, an application of special radial motion can provide the compensation of the space charge induced mismatch at transition and make a cleaner passage through transition energy. This procedure reduces the quad damper voltage and makes the operation more reliable. Eventually we should have both the voltage jump and the quad damper system to minimize the emittance growth at transition crossing.

REFERENCES

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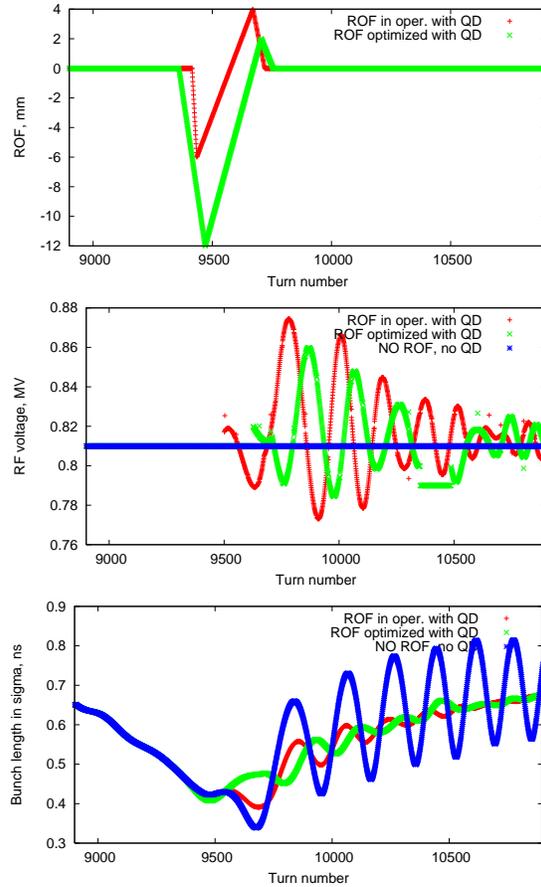


Figure 6: The radial motion (top), rf voltage (middle), and bunch length (bottom) at beam intensity of $4.5e12$ ppp for three cases: with operational radial motion and the quad damper on (red); with optimal radial motion and quad damper on (green); and without any radial motion and quad damper off (blue).

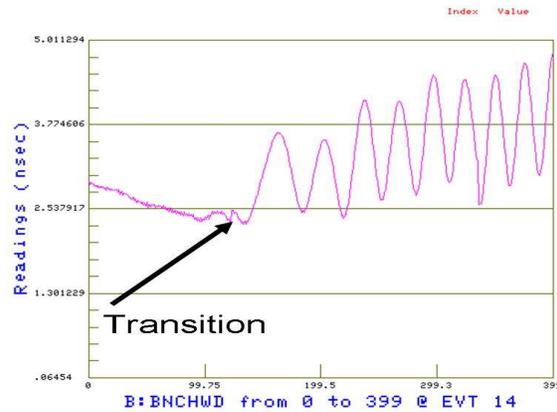


Figure 7: After implementing the radial motion at transition, the Booster 4σ of bunch length at beam intensity of $5e12$ ppp.