Reducing the Longitudinal Emittance of the 8-GeV Beam *via* the rf Manipulation in a Booster Cycle

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Abstract

Bunch rotation will cause the longitudinal emittance growth whenever there are far more A rf stations than B rf stations, or vice versa. An alternate method *via* optimizing the RFSUM curve in a Booster cycle has been investigated using the ESME simulation. Since the rf manipulation at transition crossing can reduce the longitudinal emittance 31% and the momentum spread 17%, eventually, the rms momentum spread of 2.98 MeV and the longitudinal emittance of 0.061 eV·sec with 95% of the beam can be achieved at 8-GeV.

Introduction

Bunch rotation (BR) *via* the RFSUM reduction at the end of a Booster cycle has been implemented to reduce the bucket height and area, so the momentum spread (Δp) of 18 MeV and the longitudinal emittance (ε_L) of 0.1 eV·sec with 95% of the beam can be achieved before the beam is transferred from Booster to Main Injector.[1-3] RFSUM is the vector sum of rf voltages at cavity gaps of all Booster rf stations. BR requires RFSUM to be reduced from the nominal value of 450 kV to the BR voltage (V_{BR}) of 150 kV within 10 to 20 μs, and afterwards, V_{BR} to be kept as the RFSUM voltage for a quarter of the synchronous period, about 200 μs, till the extraction. The reasons why it's difficult to keep the phase relationship between the beam and the RFSUM waveform to be constant during BR are:1st, the beam induced voltage (beam loading) intends to shift the phase of the RFSUM waveform, and such a shift increases with the decrease of the RFSUM voltage (V_{RF}) while the beam induced voltage stays nearly constant; 2nd, it takes more than one hundred microseconds for the feedback system of rf stations to compensate the beam loading, and it is slow compared to the BR time; 3rd, in the situation that one (or more) rf station is off, the A and B balancer needs to be readjusted; 4th, and furthermore, the balancer doesn't work very well when there are far more A stations than B stations, or vice versa.[3] The phase slew between the beam and the RFSUM waveform during BR often happens, and it causes ε_L growth of the beam.

It is important for us to develop an alternate method, which can be used to control Δp and ε_L of the 8-GeV proton beam. Since ε_L and Δp of the beam are determined by the bucket area (A), as shown in eq.1,

$$A = \frac{16 \cdot \beta}{2 \cdot \pi \cdot f_{rf}} \cdot \sqrt{\frac{e \cdot V_{RF} \cdot E_s}{2 \cdot \pi \cdot h \cdot |\eta|}} \cdot \alpha(\varphi_s), \tag{1}$$

and the bucket height respectively,[4] it is clear that ε_L and Δp can be controlled *via* the V_{RF} curve in a cycle. Here, β is the Lorentz's relativistic factor, f_{rf} is the rf frequency, E_s is the total energy, h is the harmonic number, η is the phase slip factor, $\alpha(\varphi_s)$ is the moving bucket factor,[4] and φ_s is the synchronous phase.

RF Manipulation

There are several important factors which need to be considered in the rf manipulation:1st, longitudinal space charge (SC) forces defocus the beam bunch before transition and focus the beam bunch after transition;[4] 2nd, since the bunch length (BL) reaches its minimum after transition, and at the same time, SC forces reach its maximum, the circumstance that the strongest repulsive SC forces lead to the particles in the beam approaching each other longitudinally accounts for the negative mass instability;[4] 3rd, and above the non-adiabatic transition crossing till BL reaches its minimum, there is a mismatch between the beam bunch and the rf bucket, which excites the BL oscillation (or called quad mode), and afterwards, the bunch starts to rotate inside the bucket and eventually occupies a larger longitudinal phase space.

For the purpose of controlling Δp and ε_L of the 8-GeV proton beam, an entire Booster cycle (33 ms) is divided into three periods: before transition from 0 ms to 16 ms

(BT); transition crossing from 16 ms to 18 ms (TR); and after transition from 18 ms to 33 ms (AT).

During BT, defocusing SC forces try to cancel rf focusing forces. Whenever SC forces are strong compared to rf focusing forces, there is likely a $\boldsymbol{\varepsilon}_L$ growth. In order to avoid (or minimize) the SC-induced $\boldsymbol{\varepsilon}_L$ growth, it is important to keep SC forces as low as possible, and this can be done *via* increasing BL since SC forces are inversely proportional to the cube of BL. Also, since lower V_{RF} is, longer BL is, BL can be maximized *via* reducing V_{RF} to the value before the beam loss starts.

RF manipulations can be implemented during TR. Since in the longitudinal phase space synchronous motions are frozen during TR, all particles with different momentums have the same revolution period, and any change in the momentum coordinate is almost decoupled from the phase coordinate. So one can increase Δp without varying BL *via* increasing V_{RF} right before transition. The benefit of increasing Δp right before transition is that such a Δp increase gives rise to the defocusing force right after transition and keeps the minimum BL away from becoming too short. Usually, when BL becomes too short right after TR, there is a significant $\boldsymbol{\varepsilon}_L$ growth due to the negative mass instability.[4] Besides, the circumstance that BL non-adiabatically reaches its minimum after transition brings a mismatch between the beam bunch and the rf bucket. Such a mismatch excites the bunch length oscillation (BLO), and causes $\boldsymbol{\varepsilon}_L$ growth. In order to keep BLO minimum, a fast increase in V_{RF} can be applied as a quad kick right after transition, since the increase in V_{RF} at a proper time will generate a defocusing in the momentum coordinate and a focusing in the phase coordinate. Two fast V_{RF} increases, or so called two rf pulses, one right before transition and one right after transition, can be applied to minimize the $\boldsymbol{\varepsilon}_L$ growth during the non-adiabatic TR.

During AT, a V_{RF} curve is optimized for the purpose of keeping Δp and $\boldsymbol{\varepsilon}_L$ of the 8-GeV proton beam minimum. Instead of applying a fast reduction in V_{RF}, which is required by BR, to achieve Δp of 18 MeV and $\boldsymbol{\varepsilon}_L$ of 0.1 eV·sec (with 95% of the beam) of the 8-GeV proton beam, a smooth reduction in V_{RF} during the last 10 ms of a cycle is implemented for the purpose of improving the operational reliability.

Numerical Investigation

ESME simulations are used to generate the optimal V_{RF} curve for the purpose of minimizing Δp and ε_L of the 8-GeV proton beam.[5] There are several important numerical investigations: 1st, the V_{RF} curve during BT needs to provide the maximum injection efficiency and a reasonably long BL in order to keep the SC-induced ε_L growth minimum; 2nd, the V_{RF} curve during AT needs to provide the required Δp=18 MeV and ε_L=0.1 eV·sec (with 95% of the beam) for the 8-GeV proton beam; 3rd, and two V_{RF} increases during TR need to be optimized in both the time and the amplitude for the purpose of keeping Δp and ε_L of the 8-GeV proton beam minimum. All the simulations were done at the beam intensity of 4.1×10^{12}, including the space charge effect.

First, the V_{RF} curve is optimized for two time periods, BT and AT. V_{RF} *vs*. time in a cycle is shown in Fig. 1(a). Here, the injection time is 0.0 ms. EPSILON *vs*. time is shown in Fig. 1(b). For a Gaussian distribution, the area containing 95% of the beam is six time EPSILON. The phase and momentum projections at 8-GeV are shown in Figs. 1(c) and 1(d) respectively. Δp (in rms) and ε_L (with 95% of the beam) of the 8-GeV proton beam are 3.58 MeV and 0.088 eV·sec.

Afterwards, the V_{RF} curve is optimized for the period of TR, while the V_{RF} curve at BT and AT stays the same with the one in Fig. 1(a), at its optimal setting. The 1st rf pulse is optimized, and the result is: 16.30 ms to 16.35 ms, V_{RF} linearly increases from 700 kV to 1000 kV; 16.35 ms to 16.95 ms, V_{RF} stays at the constant value of 1000 kV (or called flat top); and, 16.95 ms to 17.0 ms, V_{RF} linearly decreases from 1000 kV to 700 kV. The total time of the 2nd rf pulse should be relatively short compared to the synchronous period. The starting time of the 2nd pulse is varied for the optimization purpose, while the amplitude of the 2nd pulse is kept at the constant value of 1000 kV, the rising time and falling time are kept the same, 10 μs, and the time at the flat top (1000 kV) is also kept at the constant value of 80 μs. ε_L with 95% of the beam and Δp in rms *vs*. the starting time of the 2nd rf pulse, T_0, are shown as the black and blue curves in Fig. 2(a) respectively, while the 1st rf pulse is kept at its optimal setting. The charge transmission and BL *vs*. T_0 are shown as the black and blue curves in Fig. 2(b). It is clear that the optimal T_0 is 17.3 ms.

Finally, the optimal V_{RF} curve, which covers the entire cycle, is applied in the ESME simulation. V_{RF} *vs*. time in a cycle is shown in Fig. 3(a). EPSILON *vs*. time is shown in Fig. 3(b). The phase and momentum projections at 8-GeV are shown in Figs. 3(c) and 3(d) respectively. Δp in rms and ε_L with 95% of the beam at 8-GeV are 2.98 MeV and 0.061 eV·sec. Compared to the situation when the V_{RF} curve in Fig. 1(a) is used, there is a 31 %($\approx(0.088-0.061)/0.088$)) reduction in ε_L and a 17 % reduction in Δp.

Conclusions

It requires Booster to be able to deliver 8-GeV proton beams to Main Injector at the intensity of 4.5×10^{12} per batch with ε_L of 0.12 eV·sec and Δp of 18 MeV (with 95% of the beam) in order to achieve the antiproton production rate of 24×10^{10} per hour. BR has been implemented to satisfy these requirements. However, BR frequently causes ε_L growth whenever there are far more A stations than B stations, or vice versa, and the balancer doesn't work very well.[3] An alternate method *via* optimizing the V_{RF} curve in an entire Booster cycle has been investigated using the ESME simulation. Especially, the rf manipulation at TR can bring a 31 % reduction in ε_L and a 17 % reduction in Δp, so Δp (in rms) of 2.98 MeV and ε_L (with 95% of the beam) of 0.061 eV·sec at 8-GeV can be achieved.

References:

[1] K. Koba, etc., "SLIP STACKING EXPERIMENTS AT FERMILAB MAIN INJECTOR", FERMILAB-CONF-03-107.

[2] K. Koba and J. Steimel, "SLIP STACKING", FERMILAB-CONF-02-205.

[3] X. Yang, etc., "Reducing the Momentum Spread of the 8-GeV proton Beam *via* the Bunch Rotation in Booster", FERMILAB-FN-0769-AD, submitted.

[4] D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, 1993, John Wiley & Sons, Inc.

[5] http://www-ap.fnal.gov/ESME/.

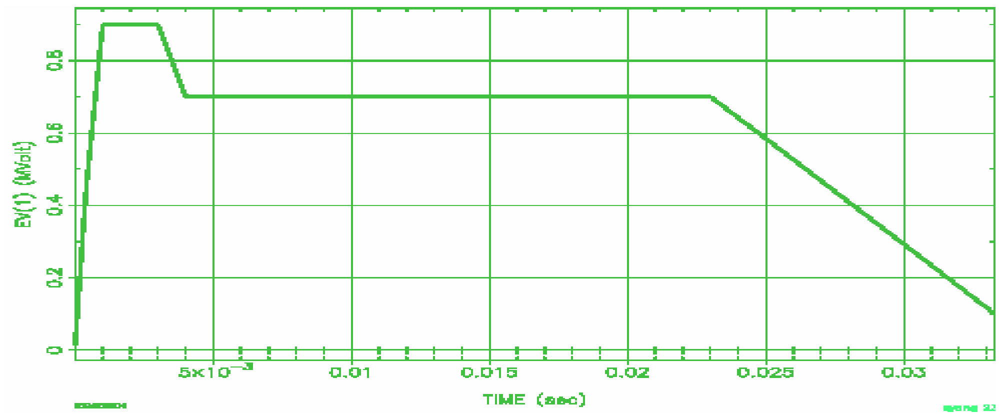
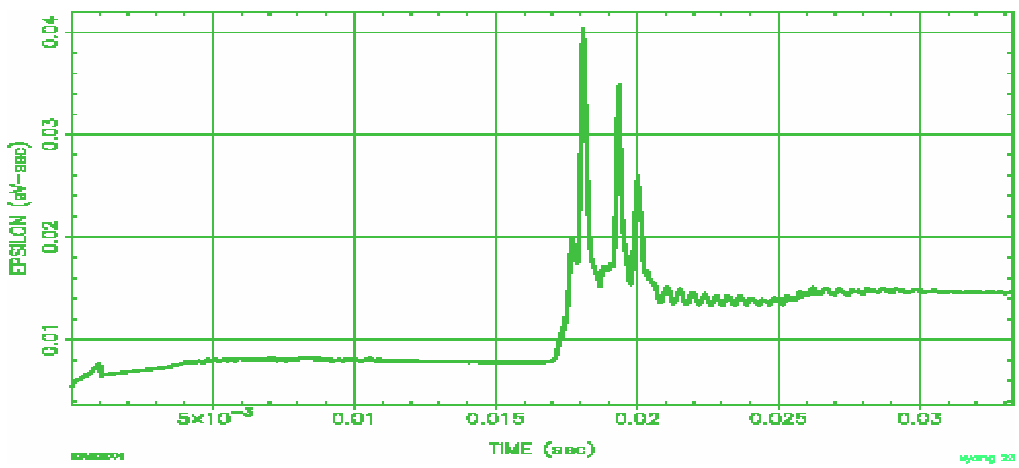


Fig. 1(a)



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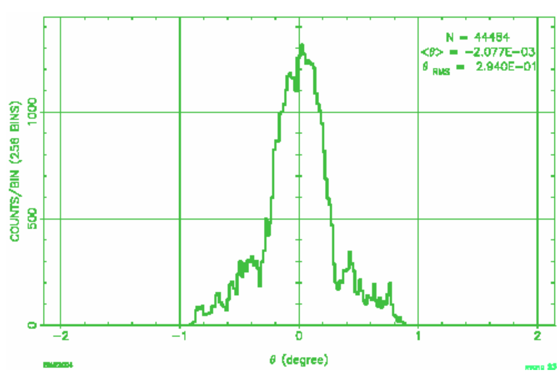

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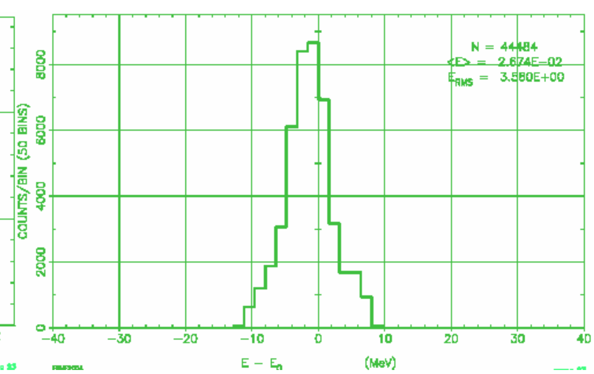


Fig. 1(d)

Fig. 1(a) V_{RF} *vs*. time in a cycle.

Fig. 1(b) EPSILON *vs*. time. For a Gaussian distribution, the area containing 95% of the beam, ε_L, is six time EPSILON.

Fig. 1(c) the phase projection at 8-GeV.

Fig. 1(d) the momentum projection at 8-GeV.

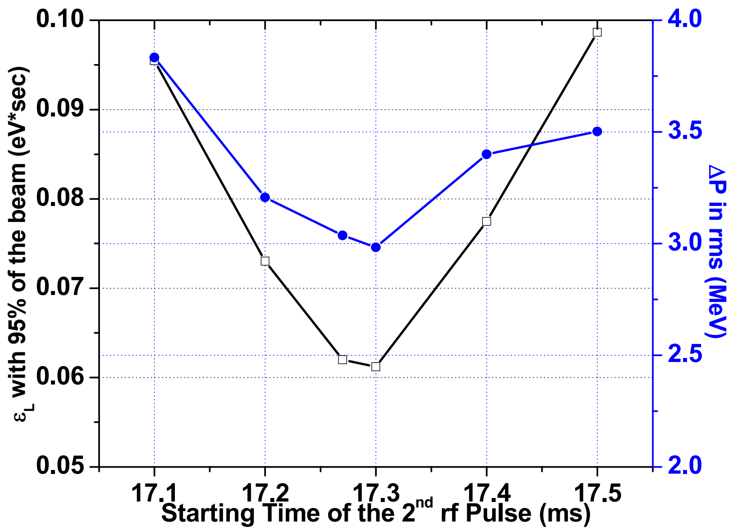


Fig. 2(a)

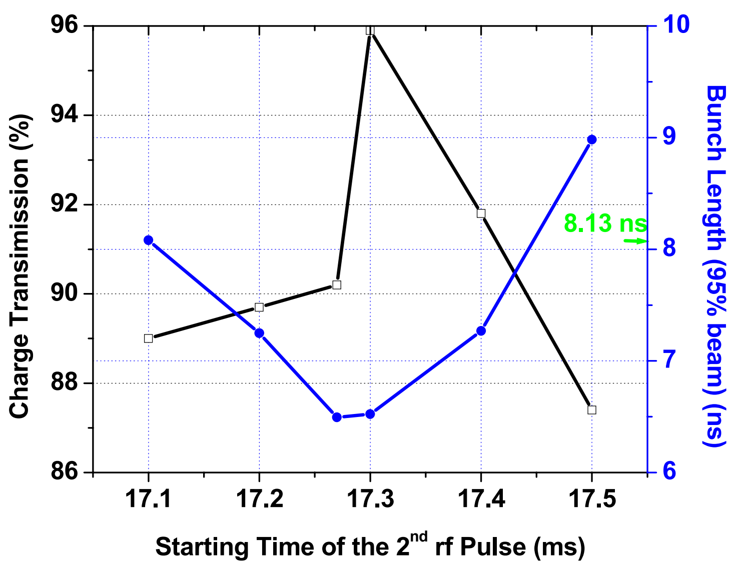


Fig. 2(b)

Fig. 2(a) $\boldsymbol{\varepsilon}_L$ with 95% of the beam and Δp in rms *vs*. the starting time of the 2nd rf pulse, T_0, are shown as the black and blue curves respectively.

Fig. 2(b) the charge transmission and BL *vs*. T_0 are shown as the black and blue curves.

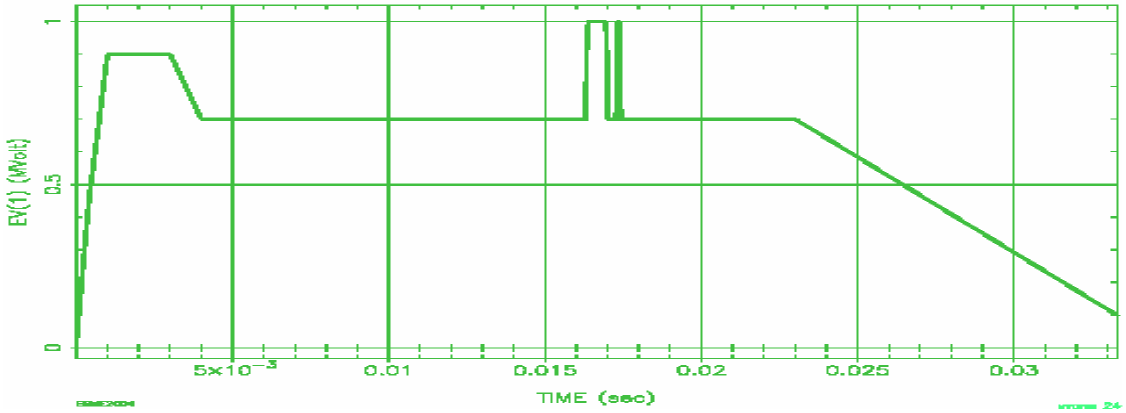


Fig. 3(a)

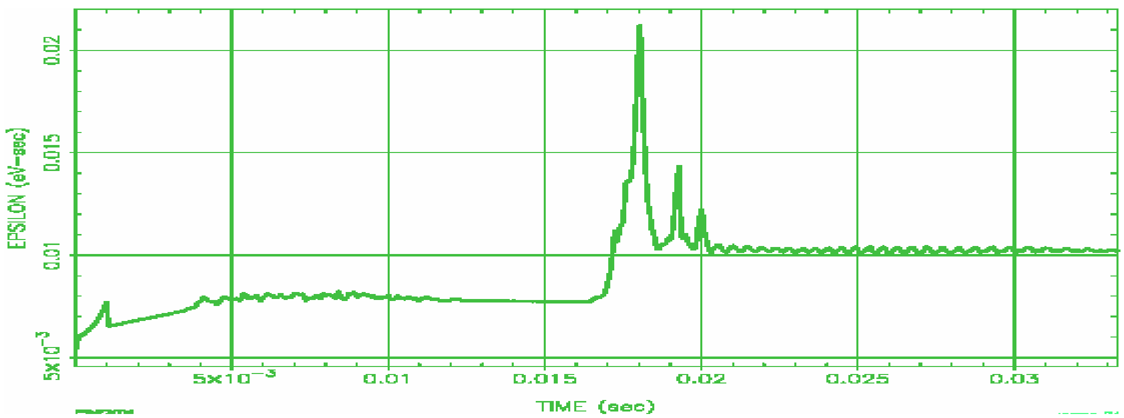
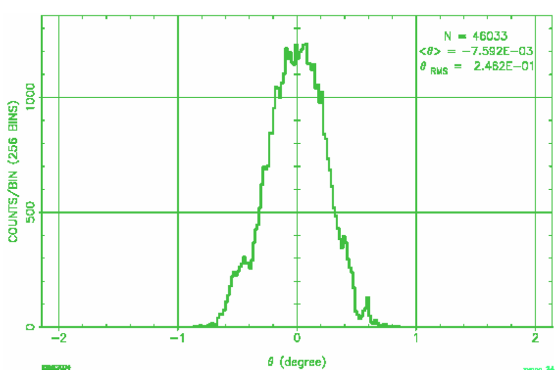


Fig. 3(b)



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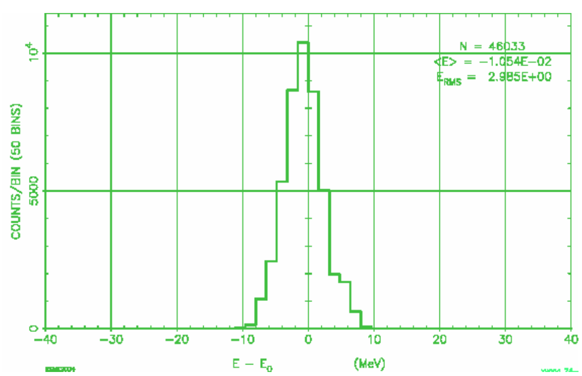

Fig. 3(d)

Fig. 3(a) V_{RF} *vs*. time in a cycle.

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Fig. 3(c) the phase projection at 8-GeV.

Fig. 3(d) the momentum projection at 8-GeV.