SLIP STACKING FOR THE FERMILAB LUMINOSITY UPGRADE

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Abstract

Increasing the proton intensity available for antiproton production is part of a plan for increasing the luminosity in the Fermilab Tevatron in the near future. We intend to increase the proton intensity using a kind of momentum stacking in the Main Injector called Slip Stacking [1]. We report the status of the effort towards its implementation.

1 INTRODUCTION

According to the current plan for Run II, the 120 GeV protons used in antiproton production will be obtained by transferring one booster batch into the Main Injector at 8 GeV and accelerating it to 120 GeV. We intend to increase the antiproton production rate using Slip Stacking in the Main Injector. This involves stacking two booster batches end to end but with slightly differing momenta, into the Main Injector. The two batches have different periods of revolution and 'slip' relative to each other azimuthally and finally overlap.

The fractional difference in periods of revolution for the two batches is given by

where $\frac{\Delta p}{p}$ is the fractional momentum difference and η is the slip factor. The slip factor is given by

$$\frac{\Delta\tau}{\tau} = \eta\frac{\Delta p}{p} \tag{1}$$

$$\eta \equiv \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \tag{2}$$

For the MI, $\gamma_t = 21.8$ and at injection, $\gamma = 9.55$. and $\eta = 8.86 \times 10^{-3}$. The duration of a booster acceleration cycle, T = 66.7ms. At injection, the length of a booster batch l = 1.57 μs, and the period of revolution in MI, τ = 11.14 μs. If the two batches are injected 46 MeV apart and allowed to slip, they would overlap completely after half a Booster cycle, i.e., 33 ms.

When they overlap they are captured using a single rf which is the average of the initial frequencies associated with the two batches. The two batches might be moved closer together in momentum if a smaller longitudinal emittance for the final beam is desired. Since the booster and Main Injector acceleration cycles are 66ms and 1.5s respectively, we expect a substantial increase in the pbar production rate, if the process can be completed efficiently.

2 RF MANIPULATIONS

The following is a list of factors that determine the optimum momentum separation between the two batches, initially and just before they are coalesced, and the rf voltages involved.

1) A larger momentum separation reduces the time before the batches can be coalesced.
2) A larger momentum separation requires a larger horizontal aperture.
3) A smaller momentum separation just before the batches are coalesced leads to a smaller longitudinal emittance for the final beam, if the effect of the second rf system is small.
4) The rf buckets for the two batches get more distorted as the separatrices move closer together. The losses become fairly high if the separatrices overlap. So the beams should spend as little time with their separatrices close together as possible before they are coalesced.

The procedure used to find rf curves that would result in a coalesced beam of small emittance containing a reasonably large fraction of the initial beams, is described elsewhere[2]. A set of acceptable rf curves is shown in figures 1a -1d. Figures 1a , 1b, 1c and 1d show the variation, before coalescing, of

1) the rf voltage for either of the two original beams,
2) the bucket height for either of the two original beams,
3) the separation of the frequency of one of the two beams from the mean of the two frequencies before coalescing, and
4) the synchronous phase angle for one of the beams

respectively. The mean of the two frequencies before coalescing is constant through the RF manipulations and is the same as the frequency used for coalescing.

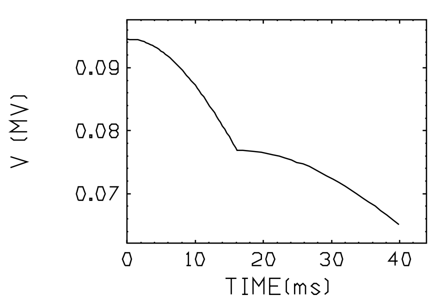

Figure 1a : Variation of rf voltage for either beam.

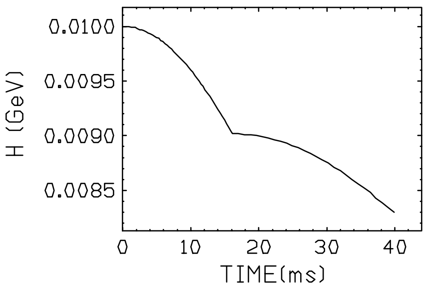

Figure 1b : Variation of bucket height for either rf.

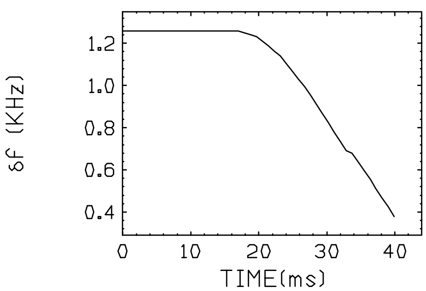

Figure 1c : Variation of the separation of one frequency from the mean of the two frequencies.

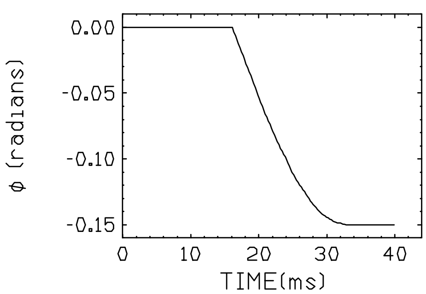

Figure 1d : Variation of the synchronous phase for one of the two beams.

Fig. 2 shows the particle distributions just before coalescing in simulated beams of low intensity subjected to the rf curves depicted in figures 1a-1d. The rf buckets corresponding to the two frequencies just before coalescing are also shown. The two beams are captured with a single rf while they are still accelerating. The efficiency of acceleration and coalescing for a final longitudinal emittance of 0.34 eV-s is 95%. The shape of the final bucket is shown in the figure as the solid line. The dashed curve inside the final bucket is a contour containing 0.34 eV-s of area. The distributions were obtained ignoring all collective effects including beam loading.

At higher intensities, some of the collective effects are expected to become important. We have investigated the longitudinal space charge effect and the effects of beam loading in the rf cavities. We find that the beam loading voltage is high and will have to be compensated for.

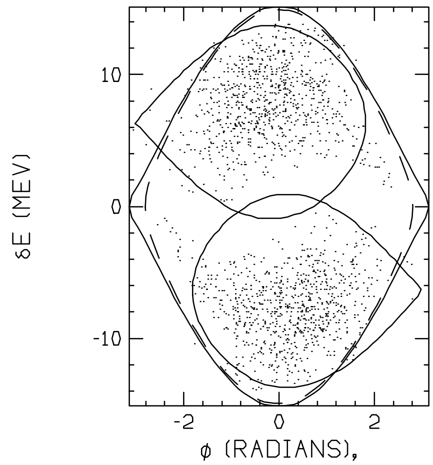

Figure 2: Beam distributions just before coalescing.

3 BEAM LOADING

If the quality factor, Q, is high and the bunch length is short, the cavity voltage V(t) following the passage of a bunch of charge *q* is given by

$$V(t) = \frac{q\omega_r R}{Q} \; e^{-(\alpha+i)\omega_r t} \qquad (3)$$

where R is the cavity shunt impedance, ω_r is the cavity resonant frequency, and $\alpha=1/2Q$.

In the case that the bunches are spaced by $\tau=2\pi/\omega_r$, the voltage after the passage of n bunches is easily found to be

$$V(n\tau) = \frac{q\omega_r R}{Q} \, \frac{1-e^{-n\pi\alpha}}{1-e^{-\pi\alpha}} \qquad (4)$$

We can apply eq.4 to estimate the beam loading voltage. As an example, we consider the case where there are two batches of 84 bunches each in the Main Injector and that the last 42 bunches of the first batch and the first 42 bunches of the last batch overlap and are exactly in phase. We ignore the difference in revolution frequencies of the two batches and the difference between the resonance frequency of the cavity and the revolution frequencies. Under these circumstances, one can use a generalization of eq.4 to estimate the beam loading voltage as shown in fig. 3. The calculation is for a total of 9 cavities with R/Q=100 Ω and Q=5000. The voltage increases when the beam passes through the cavities. During the time that the two beams overlap the voltage increases at twice the rate. When the beam is absent the voltage decays at a rate determined by the time constant α.

Approximately 0.4 ms later the bunches are out of phase and the beam voltage becomes very small.

This estimate of the beam loading voltage indicates that, if uncompensated, the beam loading voltage (1.5 MV) would dwarf the rf voltage (100 kV). Our computer simulations show that beyond bunch intensities of 4×10^9 protons/bunch, the beam loading voltage would result in loss of beam if not dealt with.

At this intensity the beam loading voltage is comparable to the rf voltage.

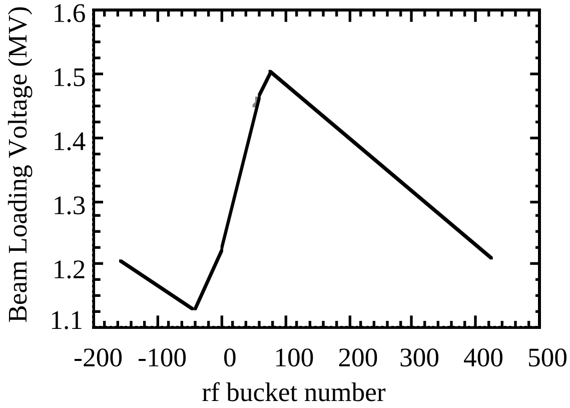

Figure 3. Beam loading voltage

We intend to control the beam loading voltage by:

1. Tuning all cavities to the nominal 8 GeV frequency.
2. Using feedforward on all the cavities. A resistive gap measures the wall current. This current, after being properly scaled, can be applied to the cavity drivers. Based on current Main Ring experience it is expected to achieve a factor of 10 reduction in the effective beam current.
3. Using feedback on all the cavities. A signal proportional to the gap voltage is amplified, inverted, and applied to the driver amplifier. This technique is expected to achieve a factor of 100 reduction (based on previous experience in the Main Ring and results achieved elsewhere).

If all these efforts are successful, beam loading should be reduced sufficiently.

4 CONCLUSIONS

The problems associated with the implementation of Slip Stacking are being studied using computer simulations and beam in the Main Ring. Based on the studies so far, beam loading voltage appears to be the most serious problem, and we are working on solving it. We plan to study the methods of reducing the beam loading voltage mentioned in Section 3 and the effects of the reduced voltage on the beam.

REFERENCES

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