Fermi National Accelerator Laboratory

FERMILAB-Conf-88/087

Bunch Coalescing and Bunch Rotation in the Fermilab Main Ring: Operational Experience and Comparison with Simulations*

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July 1, 1988

*Presented at the European Particle Accelerator Conference, Rome, Italy, June 7-11, 1988

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BUNCH COALESCING AND BUNCH ROTATION IN THE FERMILAB MAIN RING: OPERATIONAL EXPERIENCE AND COMPARISON WITH SIMULATIONS

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Abstract

The Fermilab Tevatron I proton-antiproton collider project requires that the Fermilab Main Ring produce intense bunches of protons and antiprotons for injection into the Tevatron. The process of coalescing a small number of harmonic number h=1113 bunches into a single bunch by bunch-rotating in a lower harmonic rf system is described. The Main Ring is also required to extract onto the antiproton production target bunches with as narrow a time spread as possible. This operation is also discussed. The operation of the bunch coalescing and bunch rotation are compared with simulations using the computer program ESME [1].

Bunch Coalescing

One of the important ingredients of colliding beams operation is the availability of intense, isolated bunches of particles. The coalescing process merges a number of bunches into a single intense bunch by a bunch rotation process using a lower harmonic rf system. The goal is to take between seven and thirteen h=1113 (53 MHz) bunches and produce a particle distribution which may be recaptured in a single h=1113 bucket. In the Fermilab Main Ring, the lower harmonic rf is h=53 (2.5 MHz) together with h=106 for linearizing the rotation. Figure 1 shows a picture of this process. The time spread of the rotated ensemble of particles is broadened by (i) non-linearities in the rotation, and (ii) insufficient debunching of the initial h=1113 bunches, since the rotation in the h=53/h=106 system exchanges time and energy spread.

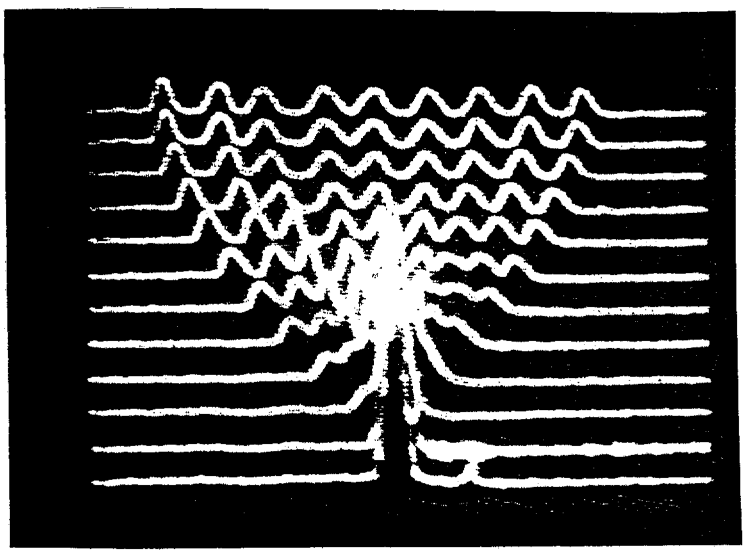

Figure 1
Coalescing

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Debunching Before Rotation

The coalescing process begins with bunches at 150 GeV in the Main Ring, and an h=1113 voltage of 800 kV. The typical intensity of each bunch is about $7\ 10^9$ for protons; for antiprotons, the intensity is about a factor of three to four lower. The longitudinal emittance of the initial h=1113 bunches in the Main Ring at 150 GeV during the 1987 Collider run was typically .20 eV-sec; this emittance would fill a bucket produced by 2270 V of h=1113. Sixteen of the eighteen rf cavities are paraphased so that their voltages cancel, and then turned off. The remaining two stations are then paraphased, reducing the voltage from 80 kV down to some low value. This two stage reduction permits finer control of the voltage towards the end of the process. Simulations (Figure 2) demonstrate the effect that reducing the voltage too quickly can have, since particles escape the bucket too early (at a large energy spread). During the 1987 Collider run, the debunching was in fact being done too quickly, a result of ramp limitations on the time available for the coalescing process.

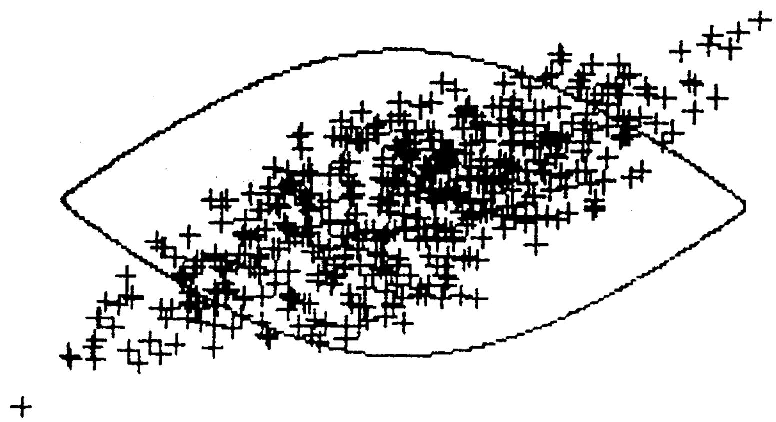

Figure 2
Debunching Too Rapidly

The present limitation in the debunching may well be an instability. Studies have been done in which the rf cavities are paraphased to produce the desired final voltage and then the voltage is held constant, with no h=53 rotation. For low voltages, below about 10 kV, the beam is observed to decelerate, preferentially from the later bunches in the ensemble, with beam loss out of the bucket continuing until there is little or no charge left in the later buckets. This phenomenon appears to have little dependence upon how slowly the paraphasing is occurring, once the process is slow enough to avoid the nonadiabatic behavior shown earlier. It also, strangely, exhibits little intensity dependence, at least over a range of a factor of four in intensity. Thus, we are presently limited to reducing the voltage to about 5 kV, and the reduction from 80 kV to 5 kV must be done in no more than 500 msec.

The ideal distribution for rotating in the h=53 system is an ensemble which is matched to a very low h=53 (or h=53 + h=106) voltage. Thus, instead of simply lowering the h=1113 voltage to some small value, one applies a few hundred volts of h=53. The voltage is chosen to provide a phase-space trajectory within the bucket which contains all the bunches in the desired phase extent and with an area equal to that of the bunches. Such a process can in principle be done with virtually no emittance blowup but requires many synchrotron periods to accomplish, at voltages far below the limitation discussed above.

One of us (PSM) has proposed augmenting the h=1113 with an h=2226 rf system 180° out of phase, which would reduce the bucket height by 18% for the same area as a bucket of h=1113 only. Figure 3 shows a simulation of beam being debunched by lowering the h=1113 voltage adiabatically to 1.34 kV while maintaining a constant h=2226 voltage of 1.53 kV, for a final bucket area of .2 eV-sec. Using the h=2226 voltage along with the h=1113 allows one, in the absence of instabilities, to get to lower energy spreads while still capturing all the beam, or lowering the voltages further to achieve additional energy spread reduction. A simulation in which both the h=1113 and h=2226 voltages were reduced by a factor of four below the full bucket values over 100 msec resulted in a final energy spread of about ΔE = 5.6 MeV, only 6% larger than the ideal 5.31 MeV. This process is much faster, and hence less susceptible to instabilities, than the process of debunching into a lower harmonic, since the synchrotron frequency varies like $\sqrt{h}$. Using the h=2226 may have a second benefit: the synchrotron period as a function of amplitude varies appreciably across the bucket, which could reduce the bunch instability problems.

Figure 3
Debunching into h=1113 + h=2226 Bucket

<u>Rotation in h=53/h=106 System</u>

The rotation in the h=53/h=106 system has been analyzed by performing separate simulations for individual bunches at different distances n from the center of the h=53 bucket, and comparing with simulations of the coalescing of the ensemble of $2n+1$ bunches from $-n$ to $+n$. Simulations were done for different values of the 5 MHz voltage, and the rotation time was allowed to vary from bunch to bunch. The RMS phase spreads after rotation are shown in Figure 4, plotted in units of angle where 2π equals the ring circumference. The right axis provides the conversion to 95% full width. The large growth in the width of the bunches with increasing bunch number when there is no 5 MHz is a consequence of phase-space conservation together with the fact that the bunch which begins at ϕ rotates to an energy offset ΔE equal to the bucket height times $\sin(\phi/2)$. As the ΔE points become closer and closer, the phase spread must increase to maintain constant emittance. The addition of the 5 MHz reduces this effect significantly.

The results of simulations of coalescing ensembles of $2n+1$ bunches are shown in Figure 5. Now, the individual bunches are all required to rotate for the same period of time, and nonlinearities will broaden the distribution. For seven bunches, one does as well with no 5 MHz; for nine or eleven, the lower value of the 5 MHz (-.18) is clearly beneficial. The bunches at ±6 are lost, however. If one increases the 5 MHz to -.20 to try to capture them, the nonlinearities increase and the resulting bunch is slightly broader when coalescing eleven bunches or less, but does better for thirteen bunches than does -.18. Higher values (-.27) are worse yet.

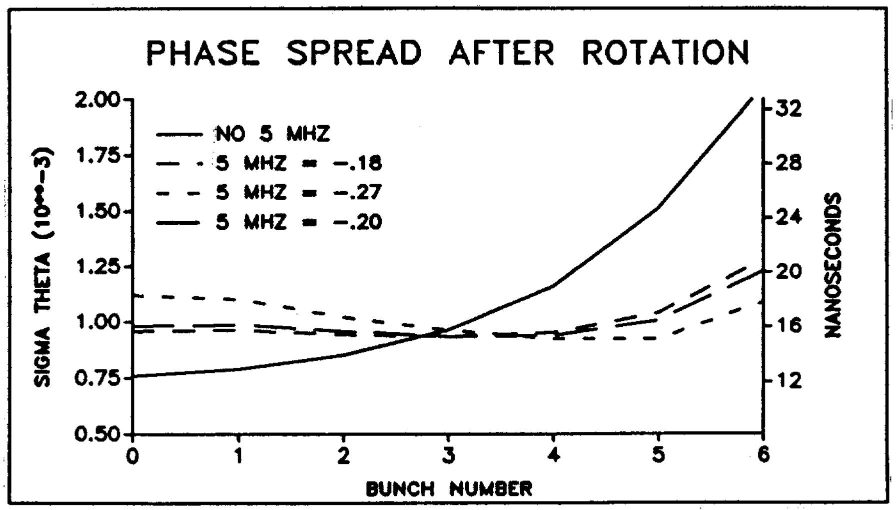

Figure 4
Rotation in h=53/h=106 of Individual Bunches

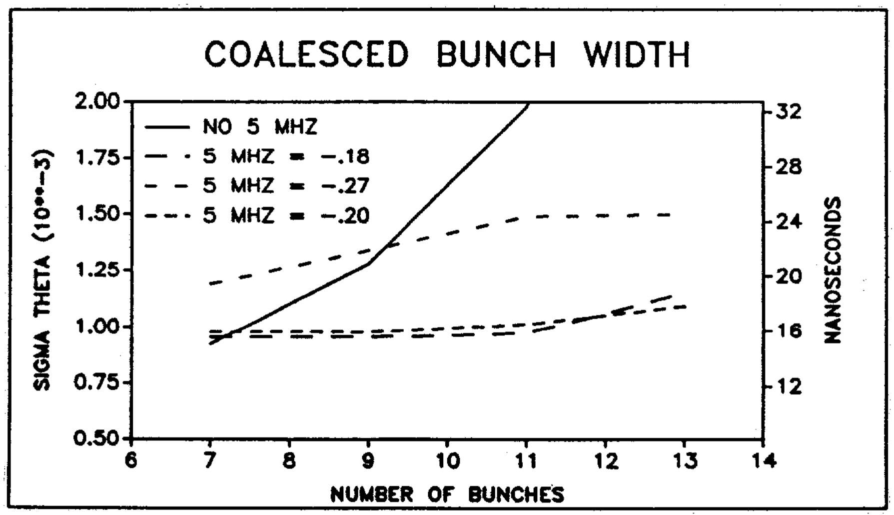

Figure 5
Rotation in h=53/h=106 of Ensembles

To evaluate the bunch-broadening effects due to the voltage waveform which is not exactly linear, one can add in quadrature the phase spreads of the individual bunches, which were plotted in Figure 4. Including only eleven bunches yields the following table:

	5 MHz=.18	5 MHz=.20
Individual Bunches	15.8 nsec	15.8 nsec
Ensemble	15.8 nsec	16.5 nsec

Table 1
Bunch Widths When Coalescing 11 Bunches

The rotation is sufficiently linearized that there is little or no difference between the individual bunches and the ensemble. The same table, but including thirteen bunches, becomes:

	5 MHz=.18	5 MHz=.20
Individual Bunches	18.5 nsec	16.5 nsec
Ensemble	18.8 nsec	17.8 nsec

Table 2
Bunch Widths When Coalescing 13 Bunches

The bunches at bunch number ±6, are broader and also lag behind the bunches just inside, reducing the recapture efficiency. Coalescing thirteen bunches will be inefficient until the debunching is improved.

Recapture in h=1113

Following the rotation by the h=53/h=106 system, the beam must be recaptured in an h=1113 bucket. An example of the capture process is shown in Figure 6. That fraction of the beam in four roughly triangular shaped regions is not captured. The particle distribution is less dense at the edges and the part of phase space which is not captured has a lower than average density. Assuming the particle distribution is parabolic in phase and uniform in ΔE, the efficiency can be determined by a numerical integration over the energy axis. An example is shown in Figure 7, which is based upon the eleven bunch, 5 MHz = -.18 rotation, for which the phase spread is 16 nsec and ΔE = 84 MeV. The fraction of particles and the fraction of the beam emittance which are captured by various bucket heights are plotted. Also plotted on Figure 7 is the ratio of bucket area to captured emittance as a function of bucket height. Since the captured beam extends to the separatrix, it will eventually fill the bucket; thus, this ratio is the expected emittance growth during the capture process. The proper voltage for recapturing depends upon the relative priorities of capture efficiency and emittance blowup, but, based on Figure 7, a bucket height around $\sqrt{2}$ times the bunch height (119 MeV) appears close to optimum. The capture efficiency increases slowly for larger bucket heights, while the emittance increases linearly. If the instability during debunching can be solved, then clearly one should try debunching into a low voltage h=53 bucket, which, after rotation, will better match an h=1113 trajectory and reduce the emittance increase.

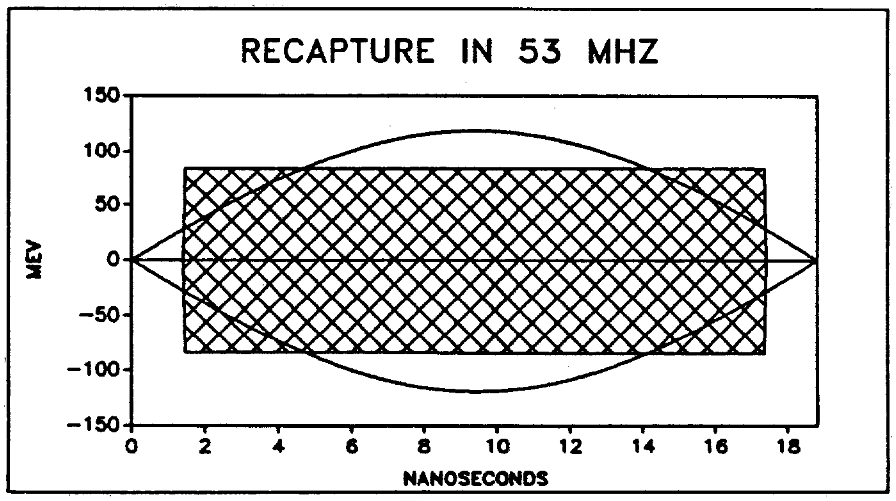

Figure 6
Recapture in h=1113

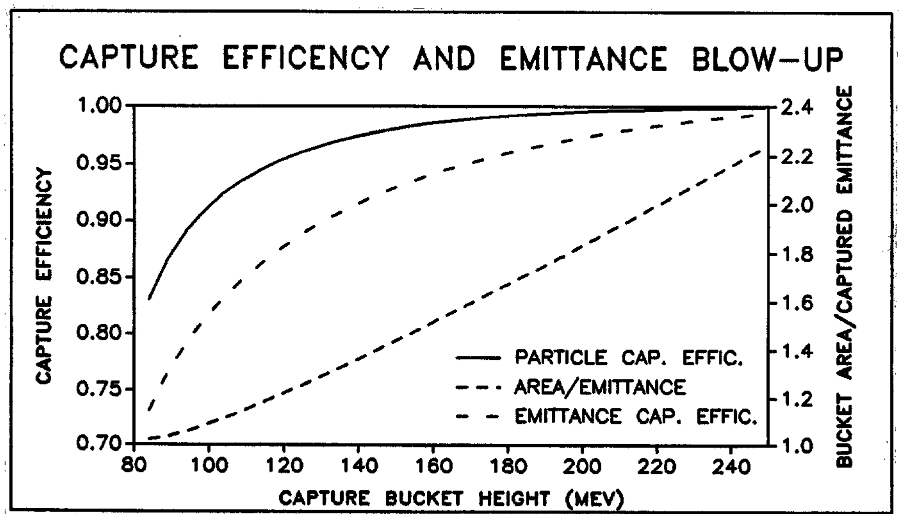

Figure 7
Capture Efficiency vs. Bucket Height

Conclusions

Recent simulations using the program ESME have shown that the debunching was being done non- adiabatically. Subsequent studies in which the rate of debunching was slowed down have shown considerable improvement in the coalescing, increasing the efficiency from about 70% to 85-90%. The present limitation is beam escaping the bucket at voltages around 10 kV. A proposal is made for using an additional h=2226 cavity which will reduce the momentum spread before rotation further (and faster) than is achievable with only an h=1113 system. Such a system might also reduce the sensitivity to bunch instabilities which may be limiting the performance, by increasing the synchrotron tune spread. The h=53/h=106 system has been shown to be suitable for coalescing up to 11 bunches. Thirteen bunches cannot be coalesced as efficiently. The recapture cannot be made 100% efficient without serious emittance blowup, but efficiencies greater than 95% should be achievable.

Bunch Rotation

The phase space density of the antiprotons produced at the target can be increased [2] if their time structure is shortened. To accomplish this, the proton bunches are narrowed by a bunch rotation just prior to extraction from the Main Ring. Two methods have been tried. The first is a simple two-fold rotation, where the rf voltage is lowered from its initial value 4 MV (V1) to about .4 MV (V2) for one quarter of a synchrotron period, then raised back to 4 MV (V3). The value of V3 is the maximum available, and produces the narrowest bunches; V1 is chosen the same for simplicity. The ratio of V2 to V1 produces a bunch which at its broadest spans nearly one-half the bucket width; this balances the nonlinearities in the rotation against the width of the bunch in the linear region. The exact ratio is emittance-dependent. (The values of V1 and V2 can be varied, provided V2 squared divided by V1 stays constant, and produce identical results. The limitation on decreasing V1 and V2 is when V2 becomes comparable to beam loading.) This procedure produces bunches which are narrower by about a factor of two than they would be if the voltage were simply increased adiabatically to 4 MV. The procedure is fairly fast: the first rotation takes less than 7 msec, the second about 1.3 msec.

The second method is to replace the first rotation by an adiabatic voltage reduction. The advantage is to avoid the nonlinearity during that part of the operation; the disadvantages are (i) the process takes longer, about 100 msec, and (ii) the voltages involved are much lower, so beam loading is more of a problem, and the desired voltage is more emittance-dependent. This technique is related to increasing the average targeting rate by accelerating multiple batches in the Main Ring. The minimum cycle time for a single batch in the Main Ring is about 2.4 sec; injecting and accelerating multiple batches which are then individually targeted can increase the average targeting rate, as shown in Figure 8. Since all batches undergo the same rf manipulations, it is desirable to decrease the nonlinearities as much as possible. Thus, the multi-batch bunch rotation procedure is approximately as follows. The voltage is adiabatically reduced from the normal 1 MV to about 75 kV until the bunches span about one-third of the bucket width. The voltage is then raised to 4 MV; after one-quarter of a synchrotron period, one bunch narrowed batch is extracted. The bunches remaining in the Main Ring continue rotating for another one- quarter synchrotron period, at which point the voltage is dropped back to the 75 kV level, and the bunches are once again matched to the bucket. The voltage is then adiabatically increased back to 1 MV until the next extraction sequence. The little operating experience to date with this technique indicates the need for better beam loading compensation.

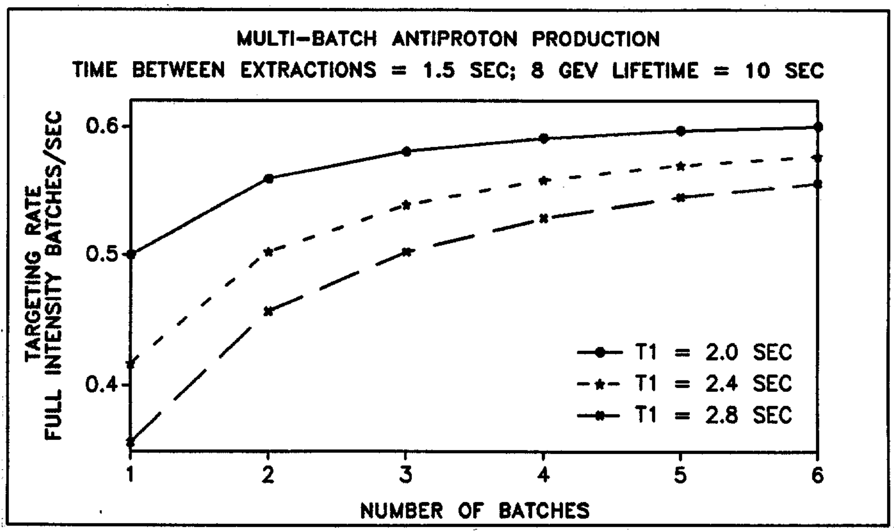

Figure 8
Multi-Batch Effective Targeting Rates

References

1. J. MacLachlan, "Particle Tracking in E-ϕ Space as a Design Tool for Cyclic Accelerators", Proceedings of the 1987 IEEE Particle Accelerator Conference, 1087 (1987).

2. V. Bharadwaj, et al. "Operational Experience with Bunch Rotation Momentum Reduction in the Fermilab Antiproton Source", Proceedings of the 1987 IEEE Particle Accelerator Conference, 1084 (1987).