IMPROVEMENTS IN BUNCH COALESCING IN THE FERMILAB MAIN RING

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Abstract

This paper discusses the improvements in the performance of the bunch coalescing operation[1] in the Fermilab Main Ring which have resulted in increased efficiency and the capability to produce bunches containing more than 10^{11} protons.

Introduction

The design bunch intensities for the Tevatron collider are 6 x 10^{10} protons and 6 x 10^{10} antiprotons per bunch. The limitation on the antiproton intensity is primarily the stack size and fraction of the stack that can be extracted and accelerated in the Main Ring efficiently. The limitation on the proton intensity is the coalescing operation. During the previous collider run, the proton intensity was typically 4 x 10^{10}; improvements in the coalescing operation have allowed achieving intensities three times this number during the present run.

The coalescing process begins by injecting a small number of h=1113 bunches into the Main Ring from the Booster or Accumulator. The bunches are accelerated to 150 GeV, adiabatically debunched and then coalesced by bunch rotating in an h=53 + h=106 rf system and recapturing in the h=1113 rf. The primary difficulty in the process is debunching the beam to a small energy spread. The bunch rotation exchanges energy spread for phase spread, and the object is to capture as much of the beam as possible in a single h=1113 bucket (whose area must be limited to avoid emittance increase.) Nonlinearities in the rotation are not important when using the h=106 to linearize the rotation, provided the number of bunches is not more than eleven.

During the 1987 collider run, there were artificial limitations on the time available for the Main Ring to accelerate beam, to phase lock to the Tevatron and align the beam for transferring to the desired bucket in the Tevatron ("cogging"), and to coalesce. The debunching part of the process was being done too rapidly, with a resulting large energy spread at the end. Typical coalescing efficiencies were 70%, and the central bunch had adjacent satellites containing a reasonably large number of particles.

Present Operation

The time limitations mentioned above have been eliminated, and the time for debunching has been extended from 0.2 to 0.9 second. Further, all the devices which are ramped for extraction from the Main Ring have had the beginning of their ramps delayed until after the coalescing operation is complete. These devices were creating closed orbit distortions which were sufficient to cause the beam revolution frequency to no longer match the rf frequency to the requisite precision. The Main Ring rf is locked to the Tevatron rf during the coalescing, and all feedback must be turned off as the beam debunches. The beam revolution frequency must remain synchronous to the rf to within a fraction of an rf cycle over the debunching time. There is insufficient bucket area during the debunching to accelerate the beam, so the momentum remains constant. With both the momentum and the rf frequency fixed, the average magnetic field must remain constant to a few parts per million in order to have the beam revolution frequency remain synchronous.

Noise, either in the rf or in Main Ring power supplies, can affect the coalescing. The deleterious effects of noise were vividly demonstrated once during this run: a power supply near the rf building had about 50 volts ripple (there are 13 supplies generating 10 kV when the Main Ring is at 150 GeV dc.) The coalescing efficiency dropped to about 25%, with large satellite bunches present, due to the power supply noise.

Additional monitors have been added which are useful in monitoring the rf and beam behavior during the debunching. One of these is a logarithmic amplifier on the rf fanback signal. This allows one to observe the behavior of the rf amplitude, which varies from 4 MV down to a few kV, accurately over this range. The previous diode-detected signal was of no use below about .8 MV. This signal has been used to assure that there is no large discontinuity in the rf as sixteen of the eighteen rf stations are turned off partway through the debunching process, and also to monitor whether the final paraphasing has gone through 180°. Another monitor which is useful is one provided by the system which damps coherent synchrotron oscillations at injection or flattop in the Main Ring. Although the feedback must be turned off during debunching, the monitor signal is useful for determining whether there are large phase errors introduced when the sixteen stations are turned off and the paraphasing of the final two stations begins.

The coalescing efficiency depends upon the longitudinal emittance of the bunches. Control of the bunch intensity is done by changing the number of turns of beam injected into the Booster. Most of the previous experience with coalescing has been with two turns in Booster. Under normal conditions, the bunch intensity is about 10^{10}, and the longitudinal emittance is about .08 eV-sec (95%). For increasing numbers of turns, both the longitudinal and transverse emittances extracted from Booster increase, along with the intensity, although with decreasing Booster efficiency. The larger emittances result in decreased Main Ring acceleration efficiency as well.

The beam-beam tune shift at 150 GeV in the Tevatron strongly affects the antiproton efficiency[2,3]. It is therefore desirable to avoid or eliminate protons which are not contained within the desired bunches. Originally this was done by requiring the coalescing to be as efficient as possible, at the expense of having less intense bunches. More recently, the Tevatron superdamper has been used to eliminate any charge not contained within the six principle bunches, prior to injecting the antiprotons. This has allowed injecting higher intensity but less efficiently coalesced bunches without the detrimental effects of uncoalesced beam. Figures 1 and 2 show the coalescing efficiency and intensity in the coalesced bunch, during one brief study period, as a function of the number of bunches injected into Main Ring and number of turns in Booster. During this study, no parameters were changed other than those shown in the plot, except for small changes in the phasing of the h=53 + h=106 system. I.e. the debunching curves were not modified, nor was the recapture time changed, to optimize the coalescing performance. Each point represents the average of 20 cycles. The consistency appeared to degrade as the intensity increased. The nine-bunch

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data seem to have an anomalously low efficiency over what one would expect. In the recent operation of the collider, the beam injected from Booster has been the 5-turn, 11 bunches; coalesced bunch intensities are typically in the range 1.1 - 1.2 x 10^{11}, with efficiencies of about 60%. Bunches as large as 1.4 x 10^{11} have been observed.

The efficiencies and intensities shown as a function of number of bunches and Booster turns seem reasonable. One would expect a decrease in efficiency, due to the increased longitudinal emittance, as the turns are increased. One would also expect a reduced efficiency, due to the narrowing of the recapture h=1113 bucket, for bunches further from the center of the distribution, i.e. for larger numbers of bunches. Simulations, however, indicate that these effects should be small. In Figure 3 the data from Figure 1 is replotted as a function of intensity in the Main Ring. Presented in this fashion, the data strongly suggest that beam-loading is the problem. The dominant problem appears to be beam-induced voltages causing phase and amplitude variations over the bunches. The result is beam falling out of the trailing buckets, at large energy spread, while it is still fully contained in the leading buckets. The beam which is lost tends to be decelerated, i.e. has a lower than average energy and upon rotation and recapture, populates a satellite which precedes the central bucket. There is also evidence of high frequency structure being induced, possibly from microwave instability, as the voltage is reduced over the last few kV.

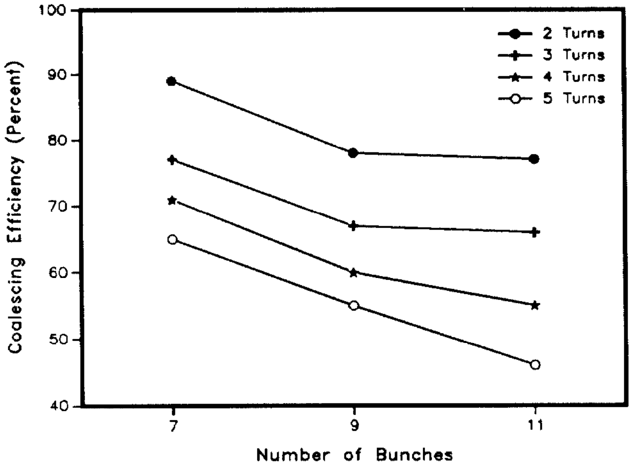

Figure 1. Coalescing efficiency vs. Booster turns and number of bunches.

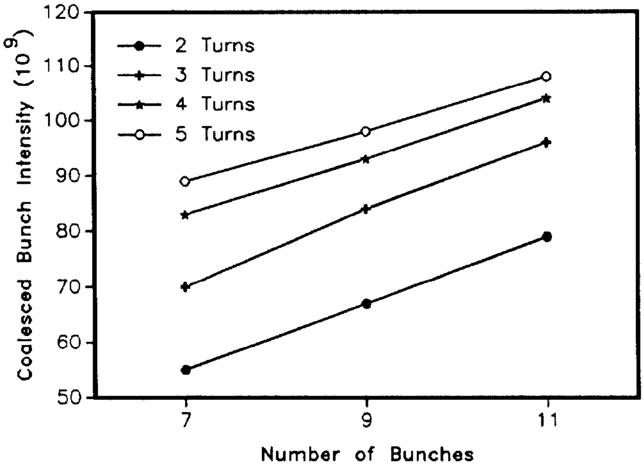

Figure 2. Coalesced bunch intensity vs. Booster turns and number of bunches.

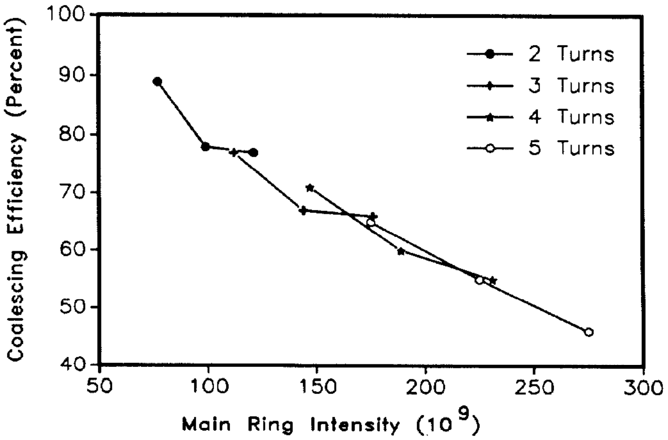

Figure 3. Coalescing efficiency vs. Main Ring intensity.

There appears to be some longitudinal emittance growth at flattop before coalescing, more for five turns than for two. Coalescing before cogging may improve the efficiency and consistency of the coalescing somewhat; it also avoids transferring unbunched beam into the Tevatron. The beam which remains in the Main Ring creates high losses at the CO experiment when the Main Ring abort fires, however, and little time has been spent studying this technique. The cogging operation did cause beam loss out of the coalesced bunch as the bunch was being accelerated to a different radius for cogging, but this has been alleviated by slowing the rate of change and hence decreasing the synchronous phase angle. There did not appear to be any adverse chromatic effects for the large-momentum spread coalesced beam as it was cogged. Coalescing before cogging would also allow more time for a decision to abort the beam in the Main Ring before the transfer to the Tevatron. This would permit rejecting low intensity bunches. Once transferred to the Tevatron, a bunch cannot be selectively aborted, nor can a new bunch be injected on top of an existing bunch with an intensity greater than 6 x 10^{10} without causing a quench.

Antiprotons have a parabolic bunch intensity profile, i.e. higher intensity for the central bunches and lower for bunches further from the center. This distribution can be recaptured after rotation more efficiently. Coalescing efficiencies for the antiprotons are in the range of 95%, compared to 70% during the 1987 run. No beam loading effects have been observed for antiprotons, for which the typical coalesced intensities are 3 x 10^{10}.

Conclusions

The Main Ring can now produce intense coalesced bunches, although the efficiency decreases as the intensity is pushed up, apparently due to beam-loading effects. This inefficiency is made acceptable by using the Tevatron superdamper to eliminate unwanted beam. Bunches of twice the design intensity can be achieved, with further improvements possible. Studies are underway to better understand the beam-loading problems and to develop cures for their adverse effects.

References

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