Operational Experience with Bunch Rotation Momentum Reduction in the Fermilab Antiproton Source

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Introduction

In the Fermilab antiproton accumulation system antiprotons are produced by the delivery of trains of 120 GeV proton bunches to a production target from which antiprotons are collected with mean energy 8 GeV (kinetic) and momentum spread $\Delta p/p > 3\%$[1,2]. The antiproton beam has the time structure of the incident protons. The proton bunch spacing-to-length ratio is made as large as possible (> 20:1) so that the resulting antiproton momentum spread may be reduced by "bunch rotation" in a "debunching" ring where time spread is exchanged for momentum spread. Details of these procedures are described elsewhere[3,4]; in this paper we report on the efficacy of these procedures during routine operation

Main Ring Bunch Narrowing

The Main Ring has been operating with a single Booster batch (~ 83 bunches) at intensity 1.5×10^{10} protons per bunch and longitudinal emittance about 0.15 eV-sec per bunch. Narrow bunches are routinely obtained by doing two successive one-quarter turn phase oscillations within unmatched buckets. During the late stage of acceleration and into the 120 GeV constant energy period the rf voltage is held at its maximum value of 4 MV. This change is adiabatic with respect to a synchrotron phase oscillation period so a matched 0.15 eV-sec bunch has a full width of about 2 ns. Starting with this condition the rf voltage is dropped to 408 kV within about 100 μs, a time short with respect to a phase oscillation period. Ideally, in one quarter synchrotron period (4 ms) the mismatched bunch rotates to span ± 60 degrees (±1.6 ns) within the bucket. At this point the rf voltage is suddenly raised back to 4 MV and the bunch rotates another quarter period so that, ignoring synchrotron tune spread, the bunch energy spread becomes ± 157 MeV and the full bunch length becomes 0.6 nsec. Recent simulations of this procedure have shown that final rotations from bunch lengths larger than ± 60 degrees are adversely affected by synchrotron tune spread and that a bunch length of about 0.65 nsec should be expected from the above procedure (±2σ with parabolic line charge distribution).

The routinely achievable quality of bunch narrowing is affected by several practical problems. Transient beam loading of the rf cavities can cause a phase shift of the buckets with respect to the beam at different locations within the batch. This selectively affects the initial broadening and subsequent narrowing. A transient beam loading compensation system[5] has been installed but there is evidence that in some circumstance it may interfere with high quality acceleration so it is not always used. Because the dynamic range of individual rf cavities is limited by a multipacting level, the voltage reduction is done by dividing the eighteen rf cavities into groups of nine and counterphasing the group to the required angle. If the angle or the amplitude of either of the groups is incorrect the resulting reduced bucket may be shifted in phase with respect to the beam bunches with adverse results. Finally, the voltage to which the rf amplitude must be lowered during the intermediate step varies linearly with longitudinal emittance. The beam quality is, in turn, a function of intensity and other vagaries of the Booster so the stated value of 408 KeV is not always correct.

In routine operation the system provides proton bunches which are reduced in length by a factor of two with respect to the bunch length in 4 MV buckets prior to narrowing. Typically bunch lengths between 0.8 and 1.5 nsec are observed. Figure 1 shows a mountain range display of the 120 GeV bunches during the last 4.5 msec prior to extraction. This display, updated at each extraction and held by a "frame grabber" is available to operators during normal operation so that the system can be optimized by minor adjustments.

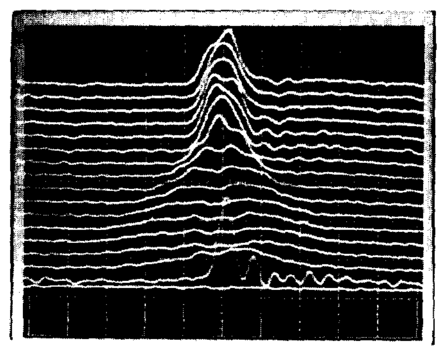

Figure 1. Main Ring bunch during bunch broadening and final narrowing for antiproton production. Time progress downward. Sweep rate 2 ns per division.

Momentum Reduction in the Debuncher Ring

The performance goal of the Debuncher ring is to reduce the relatively large momentum spread of the incident antiproton beam to less than 0.2% prior to injection of the beam into the Accumulator Ring. The Debuncher Ring has been demonstrated to have momentum acceptance of >3% with transverse acceptance of 20π mm-mr. Slightly greater antiproton accumulation rates are achieved by injecting a 4% $\Delta p/p$ beam even though the momentum reduction efficiency is not as high in that circumstance.

As an example, consider that fraction of the incident antiproton beam contained within the 3% $\Delta p/p$ (±134 MeV) and a 1 ns time interval. Such a beam would have longitudinal emittance of about 0.27 eV-sec. If this emittance were transformed such that it fills the entire 18.8 ns time period available, with no dilution, the momentum spread would transform to 0.16%.

The bunch rotation system[6,7] consists of six 53.1 MHz rf cavities generating a total of 3.9 MV. The ring operates at harmonic number 90 with $\eta=\gamma_t^{-2}-\gamma^{-2}=0.006$ so that stationary bucket height is

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200 MeV. This bucket results in rotation of the ±134 MeV distribution to ±84 degrees (±4.5 ns) in one quarter phase oscillation. In order to prevent further rotation the rf voltage must be removed when the bunch reaches its maximum time spread. Since the energy cannot be removed from the rf cavities instantaneously the rf voltage is reduced from maximum to zero during the last 50 μs. The entire quarter rotation requires about 90 μs. At this time the momentum spread has been reduced to about 0.45%. The resulting phase space distribution can be enclosed in an ellipse of about 0.33 eV-sec. Further reduction of the momentum spread is achieved by adiabatically debunching this distribution with an additional rf system which is applied just as the debunching rf is removed. This system starts at 130 kV, generating an enclosing bucket area of about 1 eV-sec, and is slowly reduced to zero over a period of 30 ms. The debunched momentum spread of the sample distribution should then match the design specification of 0.2%.

Useful representations of the momentum spread of unbunched beams in the Debuncher ring are obtained by schottky scans where the momentum spread is related to the frequency spread by $\Delta p/p=\Delta f/nf$ (η=0.006). Schottky scans are obtained around harmonic number 127 with center frequency 74.934 MHz. In Figure 2a, b, c, schottky scans are shown for the injected beam, the beam after rotation without subsequent adiabatic debunching, and the final debunched beam. In parts a and b of the figure the total frequency span is 30 kHz and in part c it is 10 kHz. The vertical scale is 5 db per division.

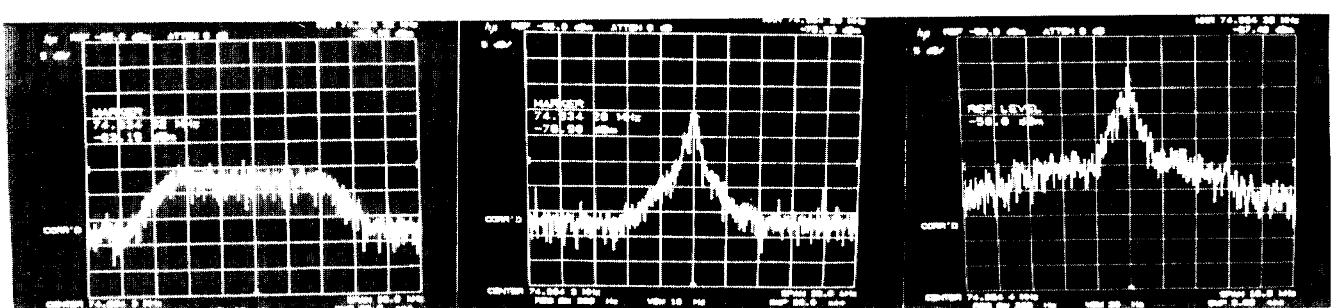
Since the total beam current within a particular schottky frequency span is a function of the detailed beam distribution within that span we take here, for illustration, the 6 db points for parts a and b and the 12 db point (essentially all of the beam for a narrow peaked distribution) for part c. In part a the frequency span at 6 db down is 18.75 kHz corresponding to a momentum spread of 4.2%. The 6 db frequency span of part b, after initial bunch rotation is 1.8 kHz making $\Delta p/p$ 0.4%. The 12 db width of part c is 1 kHz indicating that essentially all of the beam is within a 0.22% momentum range. These scans were done at a time when performance of the Main Ring and the Debuncher had been carefully optimized and consequently they represent better performance than is routinely achieved. On each cycle the final debunched schottky scan is analyzed and the fraction of beam falling within the required 0.2% momentum spread is compared to that within a 2.7% range (essentially all of the beam) and the result recorded.[9] At this time 84% of the injected beam within a 3% momentum bite is reduced to the required 0.2%. When the injected beam spans a 4% momentum range 67% falls within the required 0.2% range. Operation with 4% incident momentum spread results in a slight increase in overall antiproton stacking rate.

It is difficult to assess the absolute beam loss of antiprotons during bunch rotation because the incident negative particle beam consists of only about 2% antiprotons, the rest being e-, π-, K-, μ-, etc. The mesons are lost by decay after about five turns and the electrons by synchrotron radiation, after fifteen turns.[10] Because of the time of flight disparity it is barely possible to observe the antiproton signals between the large spurious particle signal on a longitudinal wall current monitor. By the time the spurious particles have decayed the antiproton bunch has already been significantly broadened by debunching. Attempts to integrate the area under the antiproton pulses indicate that the loss is less than 20% and is consistent with zero.

Debuncher RF Hardware Operation

In earlier discussions of this system it has been proposed that the adiabatic debuching voltage be provided by two of the debunching cavities, which were to be counterphased to provide the low time dependent voltage. This turned out not to be practical because the fine control of amplitude and phase required was frequently defeated by multipacting or other anomalous behavior of one or the other cavity. In order to provide stable and easily manageable adiabatic debunching voltage, two additional rf cavities, of a type similar to those used in the Accumulator ring for rf stacking,[11] were installed.

Operation of the six high gradient cavities and the additional lower gradient cavities has been stable and reliable. The main operational difficulty has been associated with phase-locking the system to the Main Ring rf system prior to antiproton production so that the antiproton bunches arrive properly at the bucket centers. The Debuncher rf



(a) (b) (c)

Figure 2. Debuncher Ring Schottky Scans
a) Injected beam, no rotation, span 30 kHz
b) Bunch rotated beam before adiabatic debunching, span 30 kHz
c) Final adiabatically debunched beam, span 10 kHz

All plots are logarithmic, 5 db per division must operate on a phase-lock track and hold principle, tracking the Main Ring phase until proton extraction, then locking to the proper phase and frequency during subsequent Debuncher operation. If the Main Ring rf phase changes quickly just prior to extraction, which may result, for example, from unsymmetric counterphasing or beam instabilities, then the large phase error signal which exists just at the instant of switching to hold, causes the Debuncher system to hold at the wrong frequency. The beam instabilities, which appeared to be primarily responsible for this problem during early operation, have been cured by adjustments in the Main Ring low level rf system. Errors in counterphasing remain as an occasional source of malfunction.

Another system difficulty has to do with the very slow tuning capability of the Debuncher system.[8] Because the Main Ring rf frequency is not expected to vary more than a few tens of Hertz, the automatic cavity tuning system operates by changing the temperature of the beam pipe, a slow process. However, if the Main Ring operates for a few cycles with no beam present, the frequency program errors are such that a significant detuning of the Debuncher cavity frequency can occur. Then, when beam is restored, a number of production cycles may be lost until the Debuncher rf system is retuned to the correct frequency.

These problems have been addressed in two ways. Since the Main Ring operating frequency is so severely constrained it is possible to use a voltage controlled oscillator in the Debuncher phase-lock loop which has very limited frequency range so that the system can never get very far off frequency. In addition to this, the phase-lock error signal can be monitored on each cycle and any cycle where it exceeds some present value is assumed to be a cycle on which the Main Ring either has no beam or some instability has resulted in a phase error just at extraction. In either case the frequency source to which the Debuncher system is locked can be switched "correct" default value on the assumption that the incident beam will either be absent or distorted in some way.

With the minor modifications described installed and working, the system is entirely operational and performs in a satisfactory manner.

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