

# Transverse Emittance Growth in the Fermilab Antiproton Accumulator with High-Current Antiproton Stacks

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## Abstract

Transverse emittance growth due to coherent instabilities in the Fermilab antiproton accumulator imposes a limit on the number of antiprotons which can be stacked and subsequently transferred to the collider. Consequently, the diagnosis and control of these phenomena has been required to further increase the luminosity of the collider. In this paper we present an overview of the techniques by which these instabilities have been studied and the methods by which they are controlled.

## I. INTRODUCTION

The Fermilab antiproton accumulator was designed to deliver intense  $\bar{p}$  bunches at 8 GeV kinetic energy to the main ring for acceleration and injection into the Tevatron  $p\bar{p}$  collider. The intensity of the  $\bar{p}$  bunches extracted from the accumulator is a principal determiner of the luminosity of the collider.

The  $\bar{p}$  bunches are extracted by capturing some fraction of the  $\bar{p}$  stack in a 1.25 eV•sec RF bucket, accelerating the captured beam across the accumulator momentum aperture to an extraction orbit, and kicking the beam on the extraction orbit into the transfer line connecting the accumulator to the main ring accelerator. The intensity of the extracted  $\bar{p}$ 's is therefore determined by two things: (1) the longitudinal density of the beam in the  $\bar{p}$  stack (i.e. the number of  $\bar{p}$ 's captured in a 1.25 eV•sec bucket), and (2) the efficiency of the transfer from the accumulator to the main ring. However, optimizing either or both of these can lead to transverse instabilities in the  $\bar{p}$  stack.

The criteria for transverse stability can be written in terms of the longitudinal density[1]:

$$\frac{\Delta p/p}{I_0} > \frac{eR}{4\mathbf{F}gpcQ} \left| \frac{Z_T}{(n-Q)\mathbf{h}+\mathbf{x}} \right| \quad (1)$$

The longitudinal density of the  $\bar{p}$  stack is increased by increasing the beam intensity ( $I_0$ ) and/or decreasing the momentum spread ( $\Delta p/p$ ) of the beam. It is evident from equation (1) that attempting to increase the intensity of the extracted  $\bar{p}$  bunches by doing either of these decreases the margin to transverse instability.

In addition one can increase the intensity of the extracted  $\bar{p}$  bunches by endeavoring to increase the transfer efficiency into the main ring. This can be accomplished by reducing the

transverse size of the extracted  $\bar{p}$  bunches below the admittance of the transfer line and the main ring. To this end, the accumulator is equipped with betatron stochastic cooling with sufficient gain to achieve smaller than  $1.0\pi$  mm•mrad absolute emittance horizontally and vertically for a stack size of  $10^{12}$   $\bar{p}$ 's (101 mA). There are, however, limitations to the transverse emittance reductions which can be achieved. First, the small momentum spread of the  $\bar{p}$  bunches causes a degradation in the stochastic cooling pickup to kicker mixing factor[2]. Secondly, a reduction in the transverse size of an intense negatively charged beam increases the depth of the beam space charge potential well for trapping positively charged ions, which decreases the margin to ion induced instabilities.

The combined effect of excessively increasing the longitudinal density and decreasing the transverse beam size to increase the intensity of the extracted  $\bar{p}$  bunches during collider operation is illustrated in Figure 1. This Figure shows the time evolution of the horizontal and vertical emittances after the beam has been cooled below the trapped ion instability threshold.

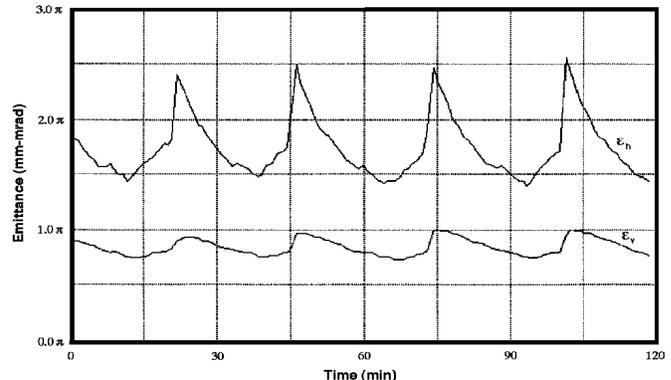


Figure 1. Transverse core emittances versus time.

The horizontal emittance undergoes a rapid 70% growth at approximately 25 minute intervals. The vertical emittance shows a similar pattern; in phase with the horizontal plane, albeit with a much smaller amplitude. The emittance growth is small enough to preclude beam loss, however the horizontal excursions give rise to emittances which are much larger than the admittance of the transfer line or the main ring. The long recovery times present serious operational difficulties during  $\bar{p}$  extraction.

A variety of techniques to simultaneously stabilize the  $\bar{p}$  stack and maximize the number of extracted  $\bar{p}$ 's have been successfully employed. These techniques include: (1) optimization of the accumulator operating point, (2) the use of wide band active dipole dampers, and (3) various trapped ion clear-

<sup>†</sup> Operated by the Universities Research Association, Inc under contract with the U.S. Department of Energy.

ing methods. A very brief survey of these techniques is given in what follows.

## II. ACCUMULATOR OPERATING POINT

There are three basic considerations vis-à-vis the accumulator operating point: (1) chromaticity, (2) the location of the tunes, and (3) coupling.

The conventional wisdom regarding the chromaticity is that it be positive to increase Landau damping of unstable coherent dipole modes, but not so large as to cause the tune spread to span a resonance. Currently the allowed accumulator chromaticity is highly constrained by the requirement that the tunes be "reasonable" throughout the 170 MeV/c (2%) momentum aperture and excellent on the extraction orbit. This requirement is due to the fact that the accumulator injection/extraction orbits and the  $\bar{p}$  core orbit are on the opposite sides of the momentum aperture; therefore, during both  $\bar{p}$  stacking and extraction, the beam is moved across the most of the momentum aperture. Also, during extraction the  $\bar{p}$  bunch remains on the extraction orbit for an appreciable amount of time (~500 msec) prior to being kicked out of the accumulator.

Because of these constraints, the accumulator is currently operated with  $\xi_H = 0.05$ , and  $\xi_V = -0.5$   $\{\xi \equiv dQ/d(\Delta p/p)\}$ . In the future there are two items which may improve the chromaticity situation: (1) an upgrade in the octupole circuit power supplies which will allow more compensation for the tune excursion due to chromaticity, and (2) a redesign of the accumulator extraction lambertson which currently has an appreciable affect on the extraction orbit tunes.

There is some small evidence that the horizontal and vertical tunes have an impact on beam stability. A beam transfer function measurement capability to obtain a quick, real-time determination of the dependence of the beam stability diagram on the tunes is being developed. To date, the systematic scan of the tunes which would be necessary to understand any relationship of the tune working point to the stability of the beam has not been completed.

The introduction of tune coupling by means of skew quadrupoles has been observed to have a stabilizing effect on the beam. A possible explanation of this may have to do with the fact that the horizontal chromaticity is close to zero; therefore horizontal coherent oscillation will see minimal Landau damping. When coupling is inserted, the horizontal plane now benefits from the much greater vertical tune spread. In practice, the accumulator is operated with the tunes uncoupled. This is done to simplify various routine diagnostic measurements. The detrimental effects of uncoupling the tunes are more than compensated for by employing any of the beam stabilizing techniques described below.

## III. ACTIVE DAMPERS

Calculations of the accumulator transverse impedance[3] indicate that a stack of  $10^{12}$   $\bar{p}$ 's will be unstable at a  $\Delta p/p$  of 0.07% (FWHM) and  $(n-Q) \leq 3$ . Therefore, the necessity of actively damping coherent transverse oscillations of the beam was recognized early in the design of the accumulator. In

practice, a horizontal and vertical damper are required for operation of the accumulator with  $\bar{p}$  stacks greater than approximately 20 mA.

The principle design requirements of the damper systems are to continuously damp transverse coherent oscillation during antiproton accumulation and extraction, and provide a flexible diagnostic tool for the study of the transverse behavior of the beam. The damper systems sense the transverse center of mass motion of the beam, amplify the resultant electrical signal, insert a delay to match the transit time of the beam and apply a correcting kick.

The damper systems consist of 0.5 meter long stripline pickups back terminated in high impedance capacitive loads to flatten the low frequency response, high input impedance differential preamplifiers, phase compensation filters and diagnostic switches, correlator notch filters to reject revolution harmonics, and power amplifiers driving 50  $\Omega$  stripline kickers. The system phase response is flat from 240 kHz (which is just below the 1-Q beam resonance) to over 50 MHz. The system gain peaks below 240 kHz due to the phase compensation filters and is flat from 3 MHz to over 50 MHz [4].

A damper system upgrade is planned for the summer of 1993. The upgrade plans include; higher impedance preamplifiers to provide flatter gain and phase below 1 MHz, rearrangement of the medium level electronics to provide for more reliable operation, and additional coupled input and output ports for improved diagnostics and closed loop beam measurements.

## IV. TRAPPED ION CLEARING

Positively charged ions trapped in the  $\bar{p}$  beam potential have been identified as the primary cause of the transverse instabilities which have been observed to date [5]. This identification prompted a concentrated investigation into a variety of ion clearing methods. The implementation of some of these methods resulted in a marked improvement in the operational performance of the antiproton source[6].

### A. Clearing electrodes

The most fundamental and effective way to remove trapped ions is the clearing electrode. Recently the accumulator ion clearing electrode system underwent a significant upgrade. The high voltage limit was extended from -100 Volts to -1000 Volts. Clearing electrodes were added to the system to clear trapped ion pockets which had previously not been cleared. There are now 140 clearing electrodes installed throughout the accumulator. The level of multiplexing in the clearing current readback has been reduced from one clearing current sum for each of the six accumulator sectors to a single readout for each two or three electrodes. The sensitivity of the current readback is at the 10 pA level, providing a powerful tool for the diagnosis of ion related phenomena. A more detailed description of the hardware upgrade is given in reference [6].

The consequent improvement in the performance of the antiproton source can be measured by comparing the minimum beam size achievable (in three dimensions) before and after

the upgrade. Figure 2 shows a plot of the minimum horizontal emittance achieved versus the longitudinal density of the  $\bar{p}$  stack.

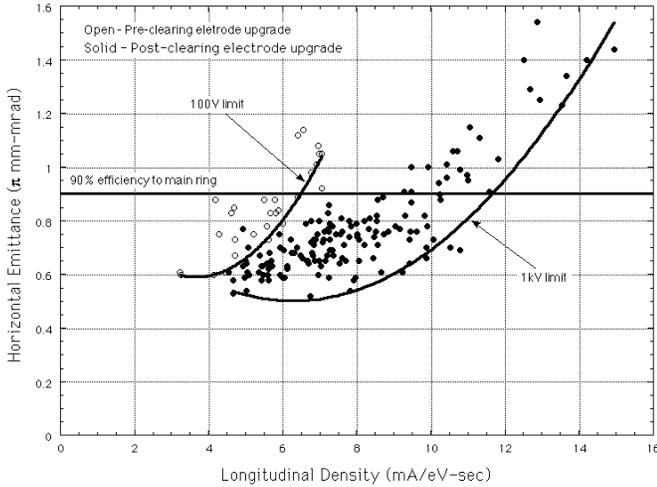


Figure 2. Transverse beam size versus longitudinal density before and after the ion clearing upgrade.

Prior to the clearing upgrade, relatively small longitudinal densities ( $\leq 7 \times 10^{10}$   $\bar{p}$ 's/eV•sec) would result in transverse instabilities. These instabilities would preclude further transverse cooling of the beam. The advent of the ion clearing upgrade increased the achievable longitudinal density by a factor of nearly 2 for horizontal emittances near the threshold for efficient transfer into the main ring.

The ion clearing upgrade prevented the periodic emittance blowups for  $\bar{p}$  stacks of less than  $120 \times 10^{10}$ . However, as is evident in Figure 2, the transverse beam size is too large for efficient transfer into the main ring at longitudinal densities in excess of  $11 \times 10^{10}$   $\bar{p}$ 's/eV•sec.

### B. Beam Shaking

Prior to the clearing electrode system upgrade, stable operation of the accumulator, during both stacking and  $\bar{p}$  extraction, required the use of beam shakers[7]. To date, this ion clearing technique involves shaking the beam at a fixed frequencies which are simultaneously close to one or more of the betatron dipole resonances of the beam and the bounce frequency of trapped ions.

Since the clearing electrode upgrade the beamshakers have had no observable operational impact and are normally turned off. There is an effort in progress to implement swept frequency beam shaking in the accumulator[8]. So far this undertaking has not progressed far enough to achieve a measurable improvement in beam stability.

### C. Longitudinal modulation of beam intensity

Bunching a small fraction (5% - 15%) of the  $\bar{p}$  beam with RF has been observed to have a stabilizing effect on the beam. This stabilization is manifested in three ways: (1) beam with emittances in equilibrium will exhibit a finite cooling rate when the RF is turned on (see Figure 3), (2) periodic emittance blowups are eliminated for intense beams (up to 135 mA), and

(3) the amplitude of the coherent betatron dipole oscillations is damped (see Figure 3).

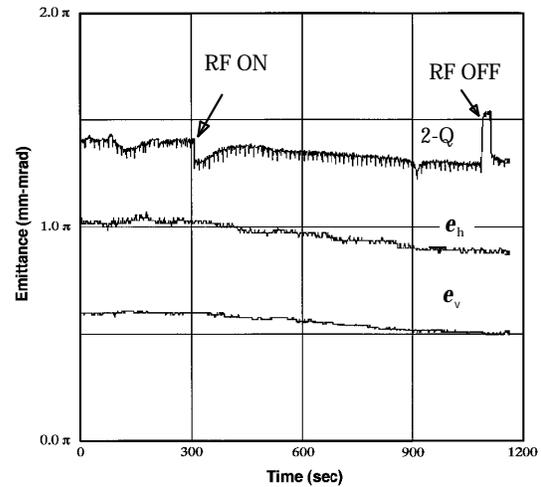


Figure 3. Time evolution of the  $\bar{p}$  beam transverse emittances and the power in the 2-Q dipole oscillation after the beam is bunched with RF.

Figure 3 shows about a 20% reduction in the transverse emittance after the RF is turned on. The lower emittance is preserved for several hours after the RF is turned off. This effect is the subject of an ongoing study[6].

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