BUNCHED BEAM COOLING IN THE FNAL ANTIPROTON ACCUMULATOR

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Abstract

Cooling of bunched beams has been explored experimentally in the Fermilab Accumulator Ring. A comparison is made between cooling rates and a simple theoretical model.

Introduction

While stochastic cooling is a routine operation at antiproton sources, it has not successfully been used in high energy colliders with bunched beams. The high densities in these machines require high cooling bandwidths to achieve even modest cooling rates. The bunch structure may result in large coherent signals which completely mask the schottky signals and make cooling impossible. Finally, the physical size of the large colliders enhances the difficulties in signal transmission. Recently, we have been investigating the possibility of bunched beam cooling at the Tevatron collider. Prototype 4-8 GHz transverse bunched beam stochastic cooling systems are presently under construction.

The Fermilab Accumulator ring normally stochastically accumulates and cools unbunched antiprotons for use in colliding beam operations. Horizontal and vertical 4-8 GHz cooling systems and a 2-4 GHz momentum cooling system are employed to cool the core (stored) antiprotons. During accelerator study periods it is possible to stack (accumulate), store, and cool protons by reversing the polarity of all the magnets. Since it is already equipped with cooling systems, has existing RF systems capable of bunching the beam, and is well instrumented, the Accumulator is an ideal accelerator to experiment with bunched beam cooling. However, the Accumulator has several significant differences from the Tevatron collider: the longitudinal beam emittance is about the same as the Tevatron but the the accumulator r.f. voltage is 38 kV (compared to 1 MV for the Tevatron) and η=.02 (compared to η=.003 for the Tevatron).

Theoretical Description

The change of betatron emittance with time during stochastic cooling is given as:

$$\frac{d\varepsilon}{dt} = -\frac{W}{N_p}\left(\frac{2g}{1+gM/2} - \left(\frac{g}{1+gM/2}\right)^2\left(M + \frac{U_o\varepsilon_o}{N_p\varepsilon}\right)\right)\varepsilon - H \quad (1)$$

where W is the bandwidth, N_p is the number of particles, and g is the system gain. The term proportional to g describes the cooling effect; the other terms describe heating effects. The schottky noise of the beam is one source of beam heating and is proportional to the mixing factor M. The mixing factor describes the correlations in the schottky noise spectrum: it ranges from a minimum of one to a maximum of infinity. The thermal noise in the amplifier feedback system also is a source of beam heating; it is proportional to U, the noise to signal ratio. The last term, H, describes heating processes such as multiple coulomb scattering and intrabeam scattering which are independent of the cooling system. We can obtain a simple solution of Equation 1 by assuming that H is a constant independent of the emittance. The solution to Eqn. 1 is:

$$\varepsilon = A e^{-t/\tau} + \varepsilon_\infty \quad (2)$$

Experimental Procedure

Transverse cooling measurements were made at three different RF voltages for the same beam. The beam intensity and longitudinal emittance were kept approximately constant. The beam was adiabatically bunched from a coasting beam at h=84 (52.831 MHz). The voltages, synchrotron frequencies and momentum spreads are given in the following table:

*Operated by the Universities Research Association under contract with the U.S. Department of Energy.

Table 1. Synchrotron Frequencies and Momentum Spreads

RF Voltage (kV)	Synchrotron Frequency (Hz)	Momentum Spread $\Delta p/p$
0	-	$.75 \times 10^{-3}$
10	365	1.03×10^{-3}
38	712	1.55×10^{-3}

Schottky Spectra Measurements

The transverse and longitudinal schottky spectra were measured at 79 MHz with resonant Schottky pickups (h=126). Figure 1 shows the bunched beam longitudinal schottky spectrum for an RF voltage of 38 kV. The spectrum shows a central line and three to four synchrotron satellite lines. The spread in synchrotron frequency, which is given by the width the of the synchrotron sidebands, can be used to determine what fraction of the RF bucket is filled. This fraction is 93% for the spectrum in Fig. 1.

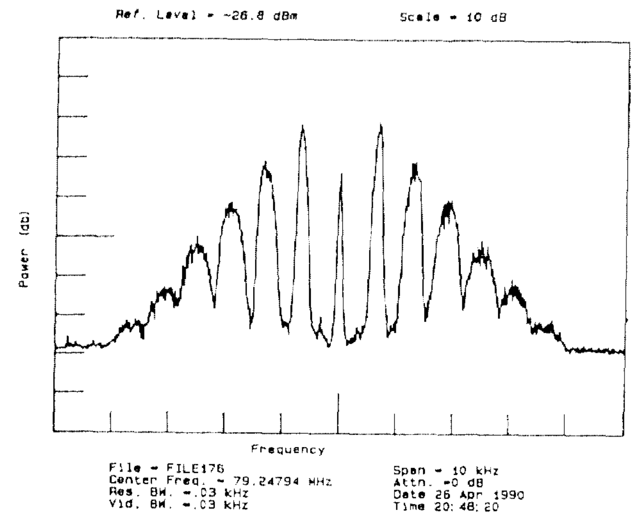

Figure 1. Bunched beam longitudinal schottky spectrum

Figure 2 shows the transverse spectrum. The width of the central line in the transverse system is dominated by the non-linear dependence of tune on amplitude, as was verified by observing the line broadening when the beam was heated. High frequency vertical betatron schottky signals were observed with the vertical cooling system pickup and are shown in Figure 3.

One of the features of the bunched beam cooling spectrum which is difficult to predict is the strength of the coherent longitudinal signals at microwave frequencies. Typical bunch shapes (such as $\cos^2$) suggest that the power of the coherent line might decay as $1/h^2$. Significant signals at multiples of the revolution harmonics were observed as shown in Figure 4. These signals were not constant in time, but fluctuated with scales of at most a few seconds. Because of their fluctuating behavior, these signals may have been the result of microwave instabilities.

Signal Suppression Measurements

When the cooling system is active, the beam motion is perturbed such that the motion of the beam as a whole (a coherent signal) tends to cancel the schottky signal (the incoherent signal). For a coasting beam the signal will be suppressed by 1 + gM/2 at the peak of the betatron sideband. Thus, the amount of suppression is a measurement of the strength of the feedback. The signal suppression is measured with the cooling system pickups and is the ratio of the schottky signal when the cooling system is off to the the schottky signal when the system is on. The average signal suppression across the cooling band for the coasting beam measurements was about 2 dB. From Eqn. 1, the ratio of the heating term to the cooling term is about 20%. The optimum ratio of

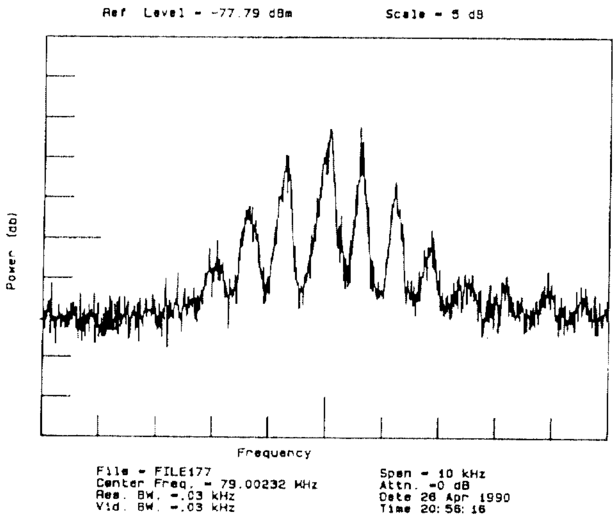

Figure 2. Bunched beam transverse schottky spectrum

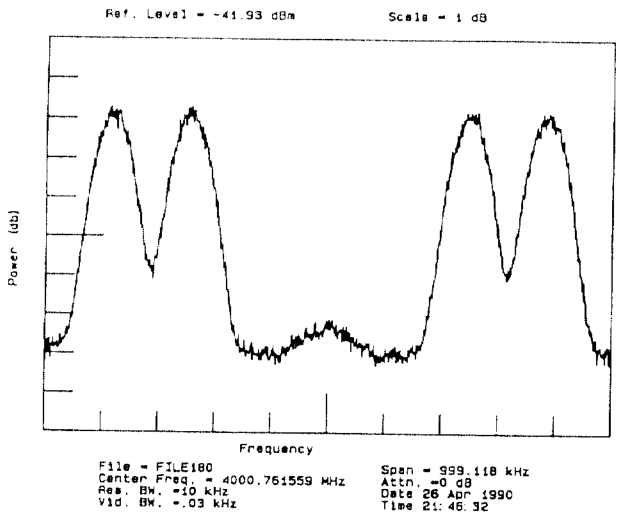

Figure 3. High frequency betatron lines for a bunched beam

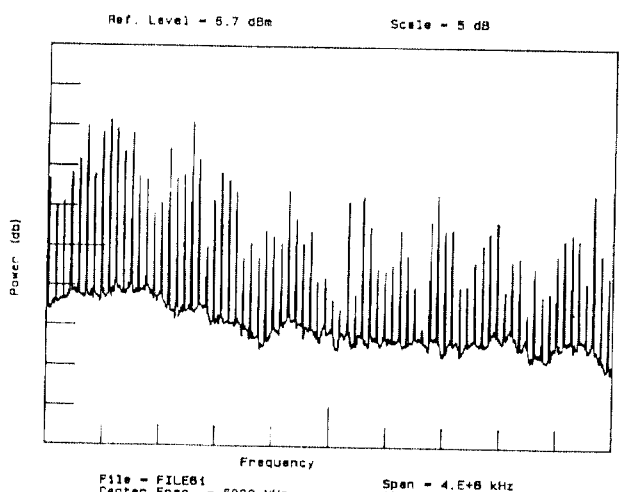

Figure 4. Broadband spectrum of transverse bunched beam signal

heating to cooling should be 50%. This ratio could not be obtained because of the lack of the necessary gain in the cooling system. This means that the effect of the bad mixing (turn to turn correlations in the beam motion) will have a small effect on the cooling rate of the beam.

The signal suppression for a bunched beam with the RF voltage = to 38 kV is shown in Fig. 5. The suppression is largest at the peaks of the synchrotron lines. The average signal suppression is about 2 dB - the same as it was for the coasting beam.

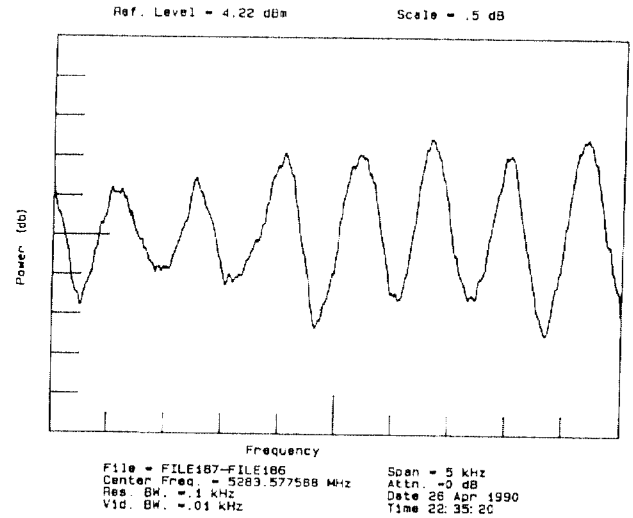

Figure 5. Signal suppression spectrum of a bunched beam.

Measurements of Cooling Rates

The uncalibrated emittance of the beam was monitored by measuring the total power in a transverse Schottky band. For all RF voltages, the beam was heated to approximately the same vertical emittance. The cooling system was then engaged and the emittance as a function of time was recorded. The data was fitted according to the expression in Eqn. 2. A plot of the data and curve fit for the emittance vs time with an RF voltage of 38 kV is shown in Fig. 6. The curve fit parameters are given in the following table.

Table 2. Cooling Rates versus r.f. voltage

RF Voltage (kV)	τ (Seconds)	ε_∞ (arb. units)
0	557	1.51
10	543	0.93
38	582	0.46

The error in τ is ±30 seconds and the error in ε_∞ is ±.06. The data in Table 2 show that there is no significant difference in cooling time when comparing bunched and coasting beam. This is not unexpected because from signal suppression measurements it was shown that the heating term is quite small due to the low gain of the cooling system. Therefore, the cooling rate is expected to depend only on the system gain and not on the momentum spread or the bunching factor.

However, the asymptotic emittance is a strong function of the RF voltage. This behavior is not predicted by Equation 1. One possible explanation for this effect could be an additional noise term due to beam instabilities. A large amount of noise generated in the kicker electrodes was traced to the fluctuations of the RF harmonics as discussed earlier in connection with Figure 5.

Network Analyzer Measurements

Vector network analyzer measurements of the system open loop gain as a function of frequency were made by inserting a network analyzer in the amplifier chain of the cooling system. The output of the network analyzer coherently excites the beam via the kicker array. The receiver of the network analyzer compares the coherent signal at the pickup array with the output signal at the kicker array. Figure 7 shows the measured response over a schottky band. Synchrotron lines are visible near the betatron tune frequency $(h \pm Q)f_0$. Figure 8 shows the synchroton lines on an expanded frequency scale.

One important use of network analyzer measurements is to measure the delay through the amplifier chain of the cooling system. This delay must equal the time of flight of the beam from pickup to kicker for the cooling system to operate properly. By selecting measurement points on the schottky bands outside of the synchrotron sidebands, the cooling system can be phased with the same technique as used with coasting beams.

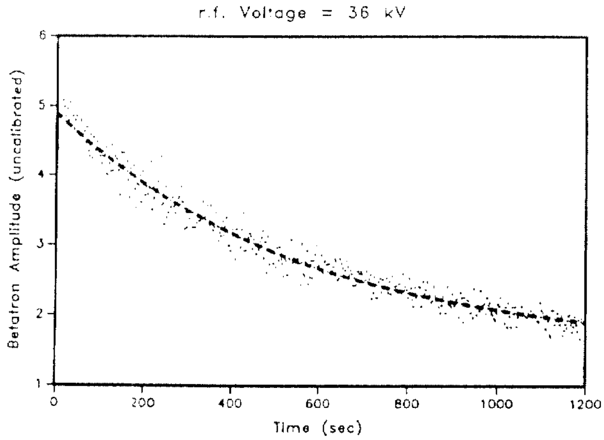

Figure 6. *Emittance vs time while cooling a bunched beam.*

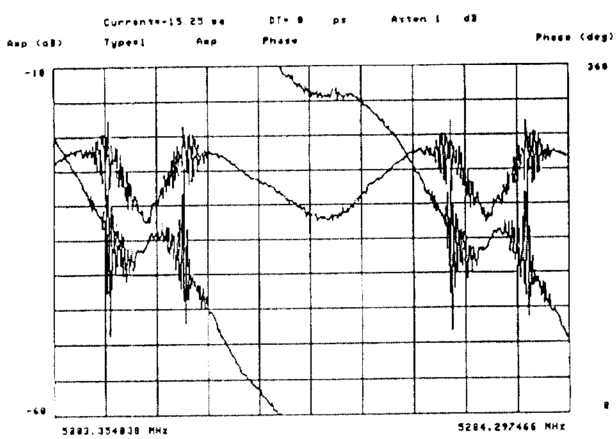

Figure 7. *Network analyzer measurement of a bunched beam.*

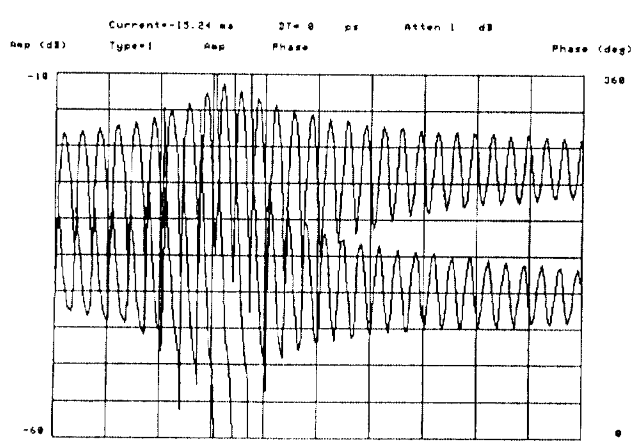

Figure 8. *Narrow band network analyzer measurement*

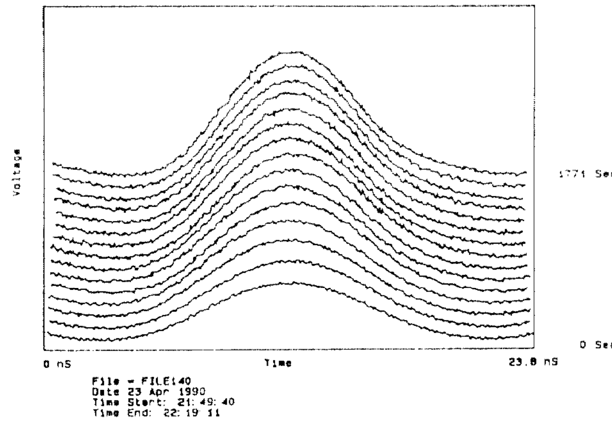

Figure 9. *Bunch profile vs time during momentum cooling.*

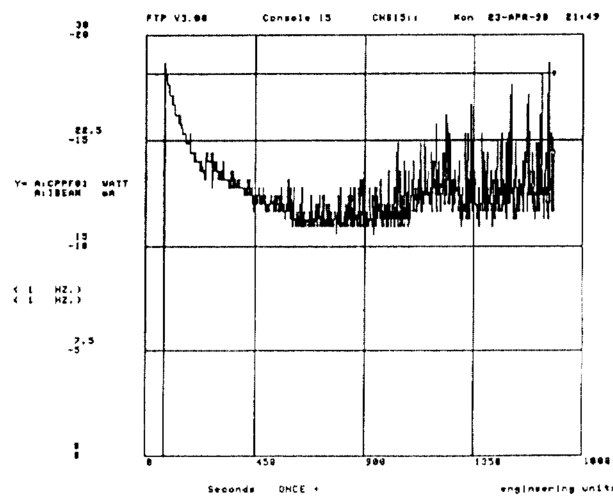

Figure 10. *Momentum kicker power while cooling a bunched beam.*

Longitudinal Cooling Measurements

Bunched beam longitudinal cooling was observed using the 2-4 GHz cooling system. This system works with a difference pickup in a high dispersion region to sense the particle momenta. Figure 9 shows a mountain range distribution of the bunch profile in the time domain. A clear increase in bunch height and a shortening of bunch width is evident as the cooling proceeds. A similar longitudal schottky scan mountain range shows the amplitude and definition of the synchrotron lines increasing. Beam that is initially outside the RF bucket is gradually enters the bucket as cooling progresses.

Figure 10 presents the power in the stochastic cooling kicker electrodes as a function of time. Initially the power decreases as the bunch length narrows. However, as the bunch length becomes narrow, the power in the kicker increased because of the increasing coherent signals.

Conclusions

This study has shown that betatron and momentum cooling of bunched beams can be accomplished with coasting beam cooling systems without modification to the existing hardware. For our low gain cooling systems, twe find no difference in the betatron cooling times for bunched and coasting beams. A simple difference pickup momentum cooling system performed effective beam cooling. However, our tests were performed for the least demanding case of nearly full buckets: there may be more severe difficulties with very short bunches.