FERMILAB RECYCLER STOCHASTIC COOLING COMMISSIONING AND PERFORMANCE

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Abstract

The Fermilab Recycler is a fixed 8GeV kinetic energy storage ring located in the Fermilab Main Injector tunnel near the ceiling. The Recycler has two roles in Run II. First, to store antiprotons from the Fermilab Antiproton Accumulator so that the antiproton production rate is no longer compromised by large numbers of antiprotons stored in the Accumulator. Second, to receive antiprotons from the Fermilab Tevatron at the end of luminosity periods. To perform each of these roles, stochastic cooling in the Recycler is needed to preserve and cool antiprotons in preparation for transfer to the Tevatron. The commissioning and performance of the Recycler stochastic cooling systems will be reviewed.

INTRODUCTION

Each role of the Recycler represents different constraints on the design of a stochastic cooling system. The design [1] of the Recycler stochastic cooling systems represents a compromise between the tasks of maintaining the phase space densities of accumulated antiprotons and pre-cooling antiprotons recycled from the Tevatron.

The cooling rates for momentum and emittance are given by,

$$\frac{1}{\tau} = \frac{W}{N}\left[2g(1-\widetilde{M}^{-2}) - g^2(M+U)\right] \qquad (1)$$

where W is the system bandwidth, N is the number of particles, g is the so called “cooling gain”, M and $\widetilde{M}$ are the mixing factors from the kicker to pickup and pickup to kicker respectively and U is the system noise to signal ratio. M is approximately 6, which implies that stochastic cooling is dominated by bad mixing in the Recycler.

Momentum Cooling

There are two different approaches to stochastic momentum cooling, the Palmer and filter methods. The design of the Recycler lattice prohibits the use of Palmer cooling. There is no appropriate location with the required high dispersion and small beam size for this technique to be feasible.

The choice of filter cooling in the frequency bands 0.5 – 1.0GHz and 1 – 2GHz was made to provide the required bandwidth. Such a system also retains a larger momentum acceptance than higher frequency systems by being less sensitive to errors that would cause feedback gain instability. However, a disadvantage is the dispersion caused by the imperfections in any notch filter system, which will cause additional heating from the momentum cooling systems.

Betatron Cooling

The initial design included the assumption of a 2π mm-mrad/hr [2] transverse heating rate. Again, a higher bandwidth system would be preferred for cooling rate. However, a larger momentum acceptance was desired for the purpose of recycling antiprotons.

A 2 – 4GHz bandwidth system, one for each transverse dimension, was chosen to implement betatron cooling in the recycler and maintain a large momentum acceptance. The pickups and kickers are located in zero dispersion regions with the betatron phase advance an odd multiple of 90°.

TECHNOLOGY

Pickups & Kickers

Room temperature phased planar loop array electrode technology [3] was chosen for the Recycler stochastic cooling pickups and kickers. Figure 1 depicts a 2 – 4GHz planar loop array composed of sixteen 100Ω loops. Half the momentum pickups operate as horizontal pickups and half as vertical pickups and placed in a high dispersion region in the Recycler lattice. The momentum kickers are similarly grouped and placed in a zero dispersion region. Therefore, it is possible to use the momentum electrodes for betatron cooling if it becomes expedient to increase the betatron cooling bandwidth (decrease the betatron cooling time) in the future. In principle, placing the pickups in a high dispersion region makes Palmer cooling possible. However, the beam size is still dominated by betatron motion where the pickups are located.

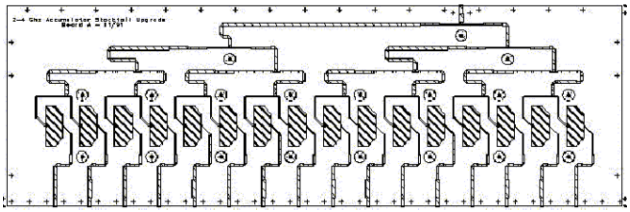

Figure 1: 2-4 GHz Planar Loop Array

Both the pickups and kickers are placed in vacuum tanks mounted on moveable stands. Centering the pickups with respect to the beam is important for both the pickups and kickers. The Recycler beam is normally bunched into a barrier bucket system. Centering the betatron pickups removes the common mode signal improving performance. Centering the momentum kickers

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minimizes whatever betatron heating is caused by a modulation of orbit length when the beam is bunched.

Transmission Line

Amplitude modulated infrared lasers [4] are used to transmit the error signals generated by the pickups to the kickers. The distance is approximately 2000ft. These optical links provide flat amplitude and phase response. For timing stability, the laser light is transmitted through a vacuum.

COMMISSIONING

There were two principal goals while commissioning the stochastic cooling systems, finding a stable operating point and increasing the bandwidth of each system. Any possible reductions in heating terms coming from the stochastic cooling systems themselves are also resolved.

One of the most important diagnostics is the beam transfer function measurement. This is a network analysis of the entire feedback circuit including the antiproton beam.

Transfer Function Measurements

A beam transfer function measurement, BTF, gives both the magnitude and phase response of the system. Figure 2 depicts a typical BTF for the horizontal betatron system. System delay between pickup and kicker is modified to make the average phase response zero across the sensitive bandwidth (3dB of maximum).

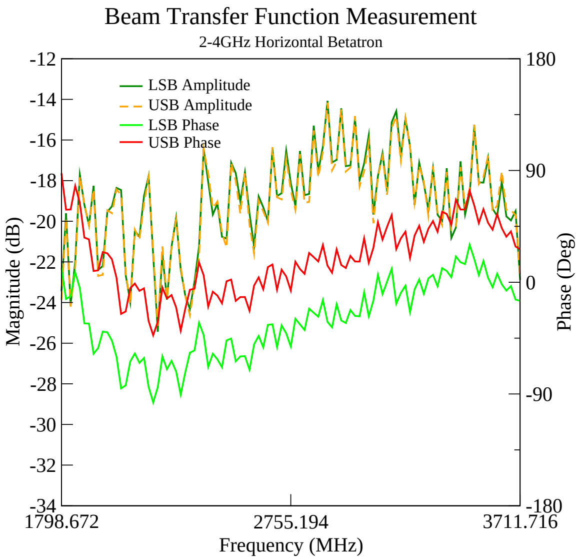

Figure 2: A “BTF” measurement. The average phase advance through the available bandwidth is zero.

BTF measurements also reveal the faults in the system. Figure 3 depicts two transfer functions. Before the installation of filters and equalizers, beam heating occurred due to low frequency system sensitivity where the phase behavior provides significant positive feedback. All systems, not just the one pictured in Figure 4, were modified several times to maximize the bandwidth and increase system stability, i.e. improve the phase response.

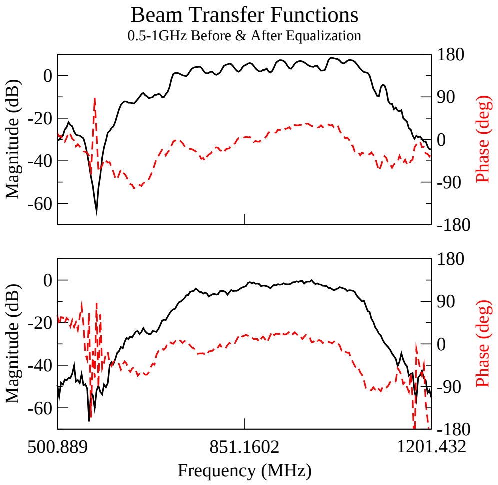

Figure 3

Tank Centering

Using the moveable stands, the cooling pickups are positioned to minimize the power output at the kickers. In addition, minimizing the common mode signal detected may also align the transverse pickups.

There are also two methods to center the kickers. Either by physically centering the kickers while monitoring beam loss, or by minimizing the signal induced out of plane. That is, by moving a momentum kicker to minimize any induced transverse signal and *vice versa*. This can again be done using a network analyzer.

PERFORMANCE

The cooling performance may be characterized by several measurements. The useful bandwidth for each system is determined from the BTF measurements. Measurement of the cooling rates combined with the BTF measurements characterizes the system performance. The cooling gain should be consistent with signal suppression measurements.

Signal Suppression

Signal suppression, the difference in the Schottky noise signals of the beam with the feedback loop opened and closed, is used as a diagnostic during operations. Figures 4 and 5 clearly show signal suppression measured at particular harmonics in both betatron and momentum cooling systems. Figure 4 also indicates one of the interesting aspects of betatron cooling in the Recycler. For the smallest momentum widths foreseeable, the betatron side bands begin to overlap at ~3GHz. These measurements, when calibrated, allow operations to fine tune the system performance regardless of the presence of systems experts.

For filter momentum cooling, the measurements are made where the Schottky signal is convoluted with the notch filter. Figure 5 shows the effect of the convolution at a particular harmonic of the revolution frequency.

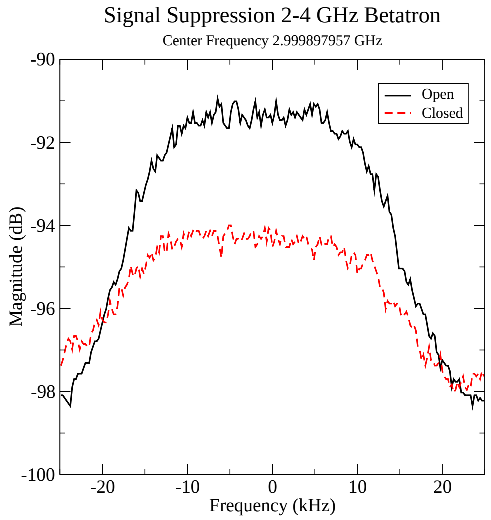
Signal Suppression 2-4 GHz Betatron
Center Frequency 2.999897957 GHz

Figure 4

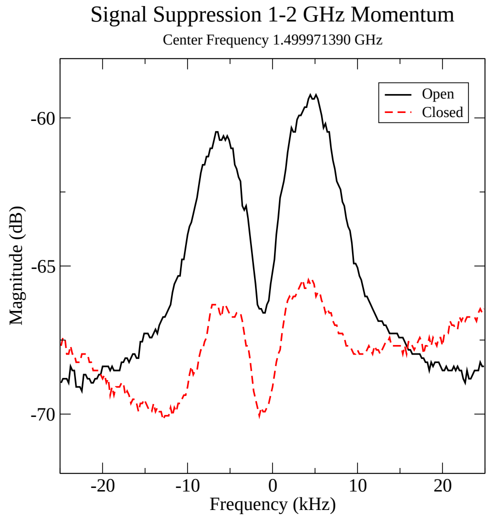
Signal Suppression 1-2 GHz Momentum
Center Frequency 1.499971390 GHz

Figure 5

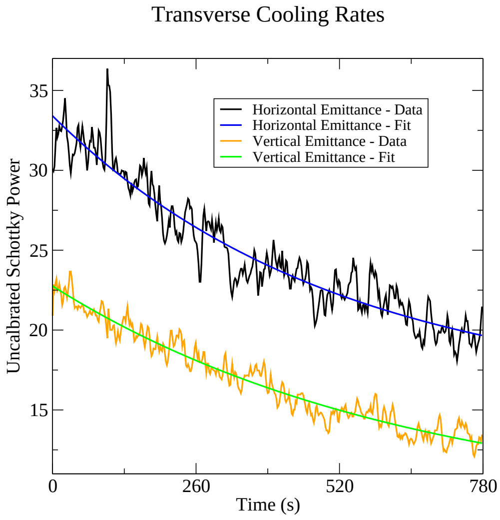
Transverse Cooling Rates

Figure 6

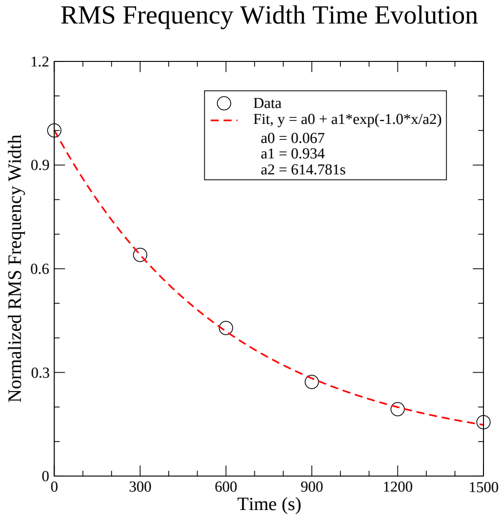
RMS Frequency Width Time Evolution

Figure 7

Cooling Rates

Recording the time evolution of the transverse emittances and RMS frequency width is a measure of the cooling rates defined in Equation (1). Figures 6 and 7 show both data and fits for transverse and momentum cooling respectively. The fit function in all cases is a constant plus an exponential decay as shown in the legend of Figure 7.

SUMMARY

Table 1 summarizes the bandwidth measurements and the cooling rates for the given number of particles. The other interesting performance parameters are the 95% asymptotic emittances. Over many attempts, the Recycler has averaged <10π mm-mrad transverse emittances and ~100eV-s longitudinal emittances for antiproton intensities from $4{\cdot}10^{10}$ to $70{\cdot}10^{10}$.

Table 1: Parameter Summary

	Betatron		Momentum	
	H2-4 GHz	V2-4 GHz	0.5-1 GHz	1-2 GHz
W (MHz)	495	715	260	674
τ (s)	516	644	615	
N	$7{\cdot}10^{10}$		$4{\cdot}10^{10}$	

REFERENCES

[1] J.P. Marriner, Fermilab MI Note 168 & 169, April, 1996.

[2] All emittances in this note are 95% normalized.

[3] "Novel Stochastic Cooling Pickups and Kickers," J. Petter, D. McGinnis and J. Marriner, Proceedings of the 1989 IEEE Particle Accelerator Conference, Vol. 1, 636, March 1989.

[4] R. Pasquinnelli, "Wide Band Free Space Transmission Link Utilizing a Modulated Infrared Laser," PAC'99, New York, March 1999, p. 7984.