STOCHASTIC COOLING IN BARRIER BUCKETS AT THE FERMILAB RECYCLER*

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Abstract

The Fermilab Recycler is a 3.3km, 8GeV/c fixed kinetic energy storage ring located in the Fermilab Main Injector tunnel near the ceiling. The role of stochastic cooling in the Recycler after the installation of electron cooling is to pre-cool the transverse phase-space of injected antiprotons for efficient electron cooling. This requires a gated stochastic cooling system working on beam confined in a barrier bucket. The performance of this system is reviewed.

INTRODUCTION

The antiproton accumulation scenario [1] for Run II at Fermilab is to transfer ~25×10^{10} antiprotons from the Antiproton Accumulator into the Recycler every 30 minutes. These antiprotons are to be within a 10eV-s by 15π mm-mrad [2] phase space volume. For electron cooling to begin working efficiently at the expected electron current in the Recycler, the transverse phase space should be ≤ 10π mm-mrad.

The Recycler uses a barrier RF systems to longitudinally isolate, for 30 minutes, newly injected beam and the cooled, higher intensity beam. Electron cooling utilizes a DC electron beam and is working on both beam segments. The role of the stochastic cooling system is to reduce the transverse emittances of the newly injected beam from 15π to ≤10π mm-mrad in 25 minutes. Therefore, the stochastic cooling is gated on the lower intensity newly injected beam so that it can be operated at the highest possible gain setting.

BARRIER RF SYSTEM

The Recycler RF system consists of four 50Ω wide band cavities. There are four class A power amplifiers which are driven by 8-bit arbitrary wave form generators. The wave form generators operate at the 588th revolution harmonic, 53MHz.

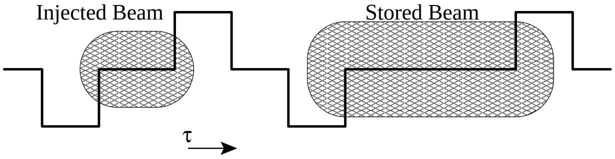

Figure 1: Two barrier buckets schematically shown with beam phase space superimposed. Each barrier voltage is a separate arbitrary wave-form in this diagram.

An example of longitudinally segmented beam is shown in Figure 1. The start position of each arbitrary wave form is broadcast on a serial link which may be received at other locations in the complex. Decoding these broadcast positions enables a generator to provide a level which follows each beam segment.

STOCHASTIC COOLING SYSTEM

The design [3] of the Recycler stochastic cooling systems represents a compromise between the tasks of maintaining the phase space properties of accumulated, dense antiproton beams and pre-cooling diffuse antiproton beams. Each role represents different constraints on the current design of the stochastic cooling systems.

The cooling rates for momentum and emittance are given by,

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

where W is the system bandwidth, N is the number of particles, g is the so called “cooling gain”, M and $\tilde{M}$ 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.

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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 [4] was chosen for the Recycler stochastic cooling pickups and kickers. Figure 2 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.

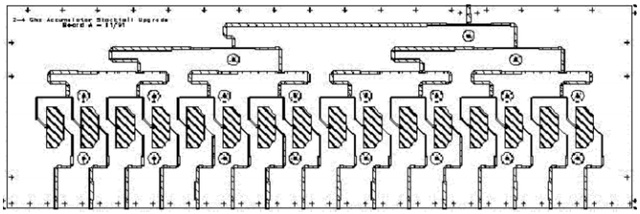

Figure 2: 2-4 GHz Planar Loop Array

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. Centering the betatron pickups removes the common mode signal improving performance. Centering the momentum kickers minimizes whatever betatron heating is caused by a modulation of orbit length when the beam is bunched.

Transmission Line

Amplitude modulated infrared lasers [5] 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 and focusing stability, the laser light is transmitted through a vacuum.

Gated Pickups

The broadcast position of each barrier bucket is decoded to make a gate. The position and width of this gate follows the motion of the barrier bucket. A pin diode switch, with switching speed better than 1MHz and 60dB isolation, is located in each cooling system. The signal from the pickup may be switched on/off many times each revolution period.

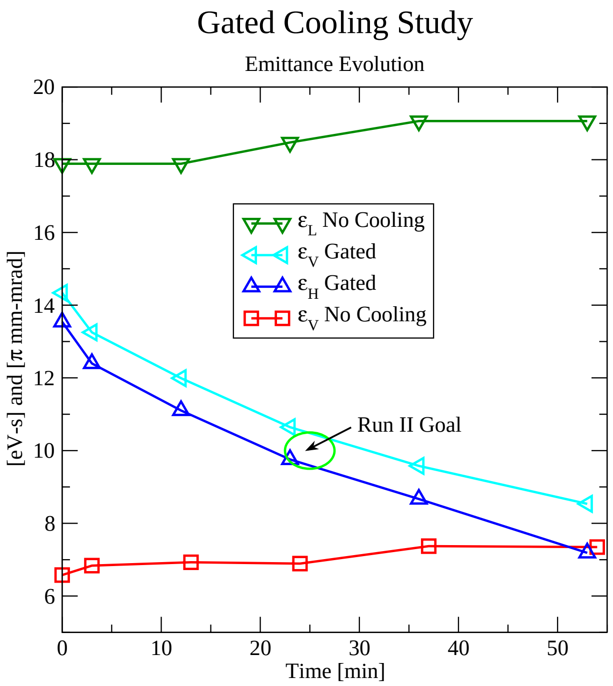

Figure 3: This study was done with two segments of beam, one cooled/gated and one not. The un-gated segment showed no emittance growth. Beam intensity was ~25×10^{10} antiprotons per beam segment.

GATED COOLING STUDIES

With the advent of medium energy electron cooling in the Recycler, the stochastic cooling system will have become single purpose. Electron cooling is more efficient when the transverse size of the proton and electron beams are similar. The Run II goal with electron cooling is for the Recycler betatron stochastic cooling systems to cool the 25×10^{10} antiprotons transferred from the Accumulator below 10π mm-mrad in 25 minutes.

The study, Figure 3, was done by segmenting 50×10^{10} antiprotons equally into two barrier buckets. The segment to be cooled was preferentially heated by tuning a gated betatron cooling system for positive feedback. Using the same gate generator as the Stochastic cooling systems, Schottky data were recorded for each beam segment every 5-10 minutes.

COOLING PERFORMANCE

Previous results were presented in [5] for smaller intensities and using uncalibrated Schottky powers. Significantly more antiproton intensity and new Schottky detectors are used for these results.

Transverse Gated Cooling Rates

Measurement of the transverse cooling rates are made by recording the time evolution of the transverse emittances as measured by calibrated Schottky detectors. The cooling rates defined by Equation (1). Figure 4

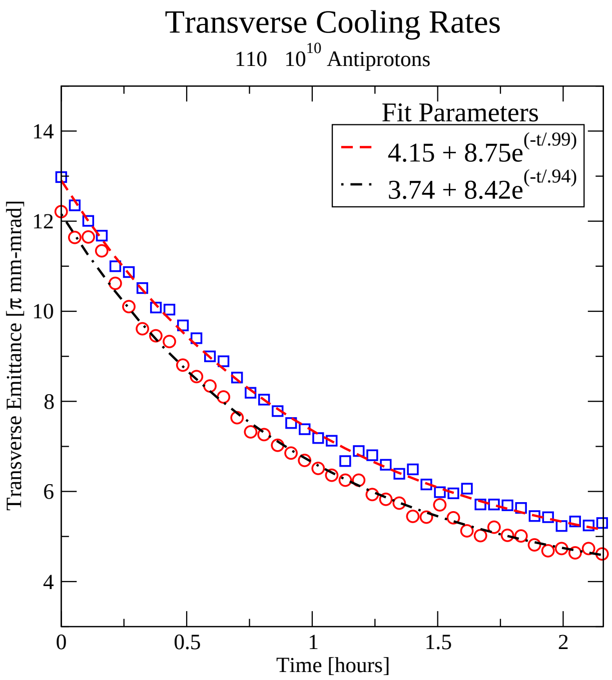

Figure 5:

shows both data and fits for transverse (horizontal and vertical) emittance evolution. The fit function in all cases is a constant plus an exponential decay. The e-folding cooling time for 110×10^{10} antiprotons is 1 hour. The previous result for 7×10^{10} antiprotons is 11 minutes. In both cases the total cooling bandwidth is the same. Several things could account for the improvement in cooling rate, system and operational improvements, better signal/noise ratio and more accurate data.

Momentum Cooling

Because the Recycler is located in the same tunnel as the Main Injector, time dependent stray fields constantly change the momentum diffusion mechanisms making cooling rate estimates problematic. Even more importantly, phase space diffusion from intra-beam scattering (IBS) dominates the momentum cooling systems.

A procedure to cool the beam longitudinally was implemented. Continually decreasing the bucket area by decreasing the separation between barriers broadens the frequency spectrum upon which the cooling system works and also keeps the longitudinal and transverse beam actions in equilibrium. Figure 6 shows the accumulated results achieved by the Recycler department using this method.

CONCLUSIONS

The current betatron systems are adequate to achieve the Fermilab Run II goals. Fast gated betatron cooling works in the Recycler. High intensity transverse cooling rates using calibrated data are presented. The asymptotic longitudinal emittance achievable in the Recycler with stochastic cooling is only adequate for current operations for beam intensities below ~80×10^{10} antiprotons.

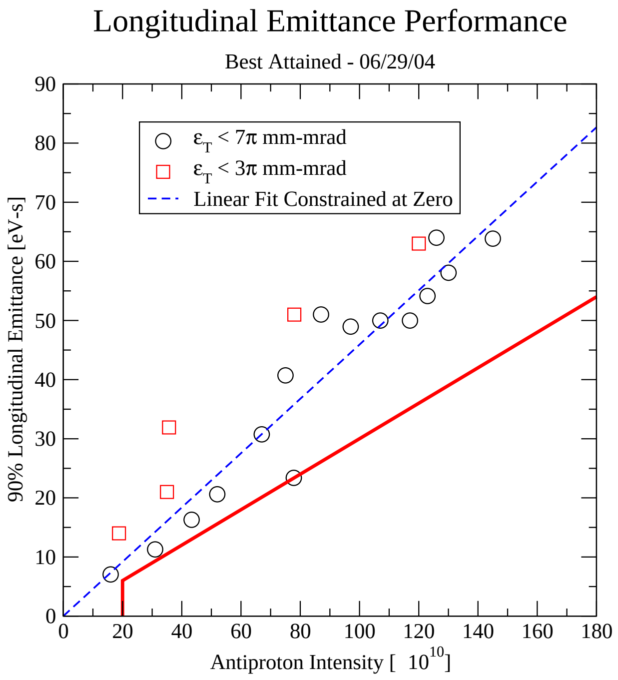

Figure 6: The solid line represents the design longitudinal emittance for the Recycler momentum cooling systems. The dashed line is the best constrained fit to the data for which the beam had ~5π mm-mrad transverse emittances

REFERENCES

[1] A. Burov, “Electron Cooling Scenarios at Fermilab,” COOL03 Workshop Proceedings, to be published in NIMA.

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

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

[4] "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.

[5] R. Pasquinnelli, “Wide Band Free Space Transmission Link Utilizing a Modulated Infrared Laser,” PAC’99, New York, March 1999, p. 7984.