STATUS OF THE FERMILAB RECYCLER*

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Abstract

I present the current operational status of the Fermilab Recycler Ring. Using a mix of stochastic and electron cooling, we prepare antiproton beams for the Fermilab Tevatron Collider program. Included are discussion of stashing and cooling performance, operational scenarios, and collider performance.

THE RECYCLER RING AT FERMILAB

The Fermilab Recycler is an 8 GeV storage ring using strontium ferrite permanent magnets. It was designed to provide more antiprotons for the Tevatron collider program, though the use of stochastic and electron cooling [1]. By providing a second storage ring for the accumulation of antiprotons and allowing for the recycling of antiprotons from the Tevatron, the Recycler was a critical part of the luminosity improvements to a design goal of $2 \times 10^{32}/\mathrm{cm}^2/\mathrm{sec}$. The Run II luminosity upgrade program expanded on this original design, requiring the Recycler to be the repository of large stashes (6×10^{12}) with appropriate phase space characteristics to be used in the Tevatron collider stores, while abandoning the plan to recycle antiprotons. In order to maximize the stacking efficiency of the Fermilab antiproton Accumulator, small stacks of antiprotons ($\approx 5 \times 10^{11}$) are transferred every 2-3 hours to the Recycler. In the Recycler, the stash is initially cooled by stochastic cooling [2], then stored and cooled by electron cooling [3] until the antiprotons are to be used in the Tevatron. Table 1 presents basic parameters of the Recycler ring. As we inject and extract with stored beam in the Recycler, we use barrier potential wells to time separate the cold 'stashed' beam from the 'hot' injected beam (or the beam for extraction).

Table 1: Recycler Ring Design Parameters

Circumference	3310.8 m
Momentum	8.9 GeV/c
Transition γ	20.7
Average β Value	30 m
Typical Transverse Emittance	6 $\pi\mu$m rad
Number of antiprotons	$\leq 600 \times 10^{10}$
Average Pressure	0.5 nTorr

ANTIPROTON COOLING

The Recycler utilizes both stochastic and electron cooling for antiprotons. Table 2 summarizes important parameters for the different cooling systems. As electron cooling can be viewed as an energy exchange process from the hot antiproton beam to the cold electron beam, achieving transverse overlap between the two beams is essential. The stochastic cooling systems are designed to cool the antiproton beam transversely, to be contained within the transverse size of the electron beam, so as to maximize the electron cooling force (see discussion in reference [4]).

Table 2: Stochastic and Electron Cooling System Parameters. There are two independent notch filter longitudinal stochastic cooling systems, in different frequency ranges.

Longitudinal Stochastic Cooling	
Frequency Range	0.5 – 1.0 GHz
Number of Pickup/Kicker loops	16
Frequency Range	1.0 – 2.0 GHz
Number of Pickup/Kicker loops	32
Operating Temperature	300 K

Transverse Stochastic Cooling	
Horizontal Frequency Range	2.0 – 4.0 GHz
Number of Pickup/Kicker loops	32
Vertical Frequency Range	2.0 – 4.0 GHz
Number of Pickup/Kicker loops	32
Operating Temperature	300 K

Electron Cooling	
Terminal Voltage	4.34 MV
Beam Current (max)	0.5 mA
Terminal Voltage Ripple (rms)	200 V
Cooling Section Length	20 m
Cooling Section Solenoidal Field	100 G
Cooling Section Beam Radius	3.5 mm
Electron Angular Spread (rms)	$\leq$ 0.2 mrad

The stochastic cooling systems were commissioned and integrated in operations in early 2003. There are two independent longitudinal systems, spanning the ranges 0.5 –1.0 GHz and 1.0 – 2.0 GHz, which use notch filter cooling. The transverse systems (both horizontal and vertical) are in the frequency range 2.0 – 4.0 GHz. All stochastic cooling systems use planar loops for pickups and kickers [5]. Gated cooling studies, to show that the systems met the performance requirements, were performed in 2004 [2]. In figure 1, I show the transverse cooling performance of the systems. They effectively cool 15π mm mrad [6] beams to 10π mm mrad within 25 minutes. Beams of

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10π mm mrad fit within the designed electron beam radius.

The electron cooling system was commissioned and integrated in operations in 2005 [3, 7]. It utilizes a 4.3 MeV DC electron beam. The beam is generated by a thermionic-cathode gun, located at a potential of 4.3 MV inside of a large electrostatic accelerator. We can sustain electron beam and voltage with currents to ground of less than 100 μA. To maintain this high efficiency, we utilize a recirculation system that has an efficiency $> 99.998\%$ for currents up to 0.5 A.

The electron gun is immersed in a solenoidal magnetic field to create a beam with large angular momentum. The beam is transported through the electrostatic accelerator and to the cooling section using convential focussing elements, then is made round and parallel to the antiproton beam such that the beam radius r_b produces the same magnetic flux as at the cathode [7]. Operationally, the electron cooler is required to reduce the longitudinal emittance from up to 140 eV-sec to $\approx$ 70 eV sec in 90 minutes for stashes up to 500×10^{10} antiprotons, which is slightly different than originally foreseen [8].

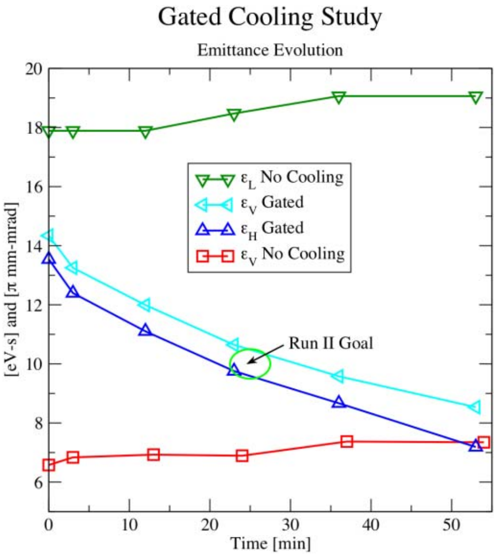

Figure 1: Gated cooling demonstration for the stochastic cooling systems. 20×10^{10} antiprotons were in a barrier potential well and the transverse stochastic cooling systems were gated to cool only the particles in that well. An additional 20×10^{10} antiprotons were in a separate potential well and were not cooled. The goal was to cool to 10πmmmrad within 30 minutes. The goal was attained, with no heating to the beam that was not in the cooled potential well.

OPERATIONAL SCENARIOS

Incoming Antiprotons from the Accumulator

The Antiproton source has made significant improvements in accumulating antiprotons through the past two years [9]. The average stacking rate has gone from 10×10^{10} antiprotons per hour to more than 17×10^{10}, with peak hours where better than 23×10^{10} antiprotons have been accumulated. There has also been significant work done in speeding up the transfers from the Accumulator to the Recycler. It is a point that often times gets lost in the shuffle, that the amount of time spent to do a transfer is time that is not spent stacking, resulting in lower total accumulation in a fixed time frame.

For transfers, we have changed our operational mindset. As antiprotons are difficult to produce, we defined success as not accepting loss of a transfer. The antiproton transfer goes from the Accumulator through a transfer line into the Main Injector, through a small energy change to match the Recycler, and into the Recycler. We did a complete detailed beam line tune up with protons from the Main Injector to the Accumulator, including the energy matching and orbit closure in the Accumulator. We had two separate sets of power supplies for the transfer line, as it is also used to transport 120 GeV protons from the Main Injector to the antiproton target, the power supply regulation at 8 GeV currents through the 120 GeV supplies was not originally good enough, and we switched supplies based on how the beamline was being used. The Run II Upgrade program included elements to improve the power supply regulation so that we no longer need to switch supplies to do antiproton transfers. The entire tuneup, plus transfers, would take on order 60 minutes, during which there was no accumulation of antiprotons in the Accumulator. To maximize performance, we would transfer when the Accumulator current reached $> 80 \times 10^{10}$ antiprotons, which required 6 separate transfers to empty the Accumulator because of bucket area constraints and longitudinal emittance in the Accumulator. Each transfer required manipulations of the barrier potential wells in the Recycler, adding time to the process. Of this 60 minutes, $\approx \frac{2}{3}$ was spent in tune up and $\frac{1}{3}$ in transferring antiprotons.

By defining success as accepting the occasional loss of a transfer, we now operate in a different mode. We use the 120 GeV beamline supplies for both protons to the antiproton target and antiprotons from the Accumulator to the Main Injector. We do a brief beamline tuneup with protons, using the efficiency of the transfer from the Main Injector to the Accumulator to define whether a more detailed tuneup is necessary (if the efficiency is $> 85\%$, we proceed). As the total preparation time is smaller, we can do transfers more frequently with less of an impact, so transfers are triggered at smaller Accumulator currents ($> 50 \times 10^{10}$ antiprotons). As the current is smaller, the Accumulator stochastic cooling systems are more efficient, lowering the longitudinal emittance and requiring fewer transfers to empty the Accumulator. With fewer transfers, the time for the barrier potential well manipulations is also smaller. We know routinely do the transfers in $\approx$ 12 minutes, with the same $\frac{2}{3}$ $\frac{1}{3}$ split between setup and transfer, with 3 separate transfers from the Accumulator to the Recycler. We estimate (given caveats discussed below with regard to inten-

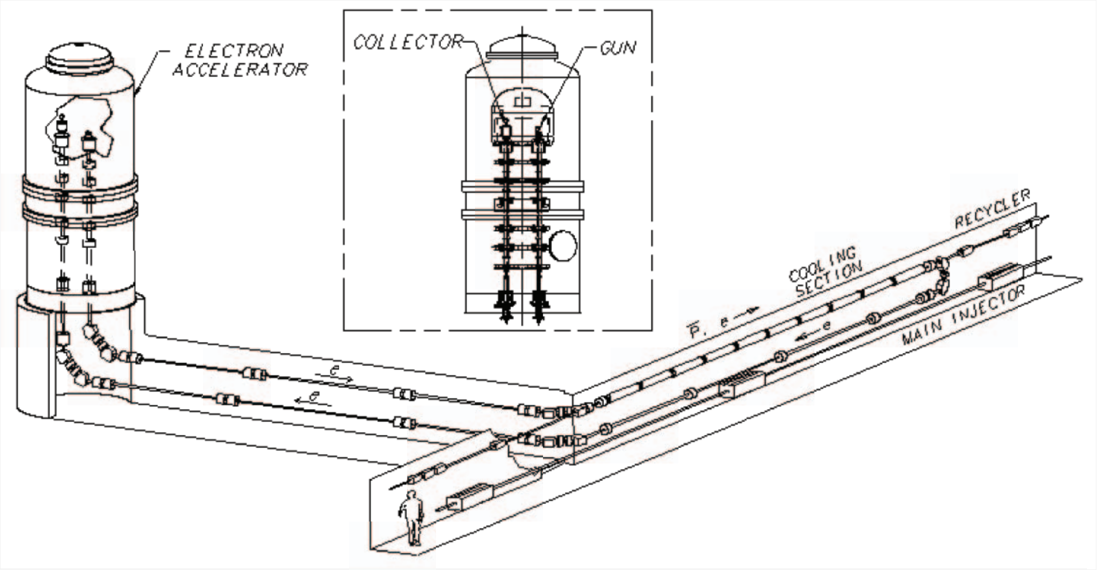

Figure 2: Electron Cooling insert in the Fermilab Recycler.

sity measures) that the transfer efficiency is $\approx 90\%$, falling slightly as intensity in the Recycler increases.

Figure 3 shows an operational week for the Recycler. In the top plot, the Recycler beam intensity is in red, the Accumulator beam intensity is in blue, and the sum is in green (all in units of 10^{10}). During this 7 day period, there were 52 transfers from the Accumulator to the Recycler, with the peak Accumulator current of $\approx 75 \times 10^{10}$ but most occurring at 50×10^{10}. There were 4 transfers to the Tevatron during this week, with Recycler current routinely $> 300 \times 10^{10}$ and peak current $> 450 \times 10^{10}$ antiprotons. There was one lost stash in the Recycler, due to a failure in a CAMAC controls crate that included the control cards for ramped trim dipoles (used to compensate for changes in the path length due to the ramping of the dipole and quadrupole busses in the Main Injector). In the bottom plot, red is the horizontal transverse emittance and blue is the vertical transverse emittance for the antiproton beam in the Recycler. Note that we were consistently able to keep the transverse emittances between 5 and 7 π mm mrad, even as the intensity reached its maximum.

Of interest in figure 3 is the behavior of the beam intensity in the Recycler between transfers from the Accumulator. One would expect the intensity to decay during this time period, due to finite beam lifetime. Close inspection of the intensity shows that it in fact rises in between transfers! Are we making antiprotons out of the vacuum? No, of course we are not. In December 2006, the main beam current measuring device (a DCCT) for the Recycler failed. We did not have a replacement in hand, so we needed an alternative method of measuring the beam current. The DCCT was the only instrument capable of making a DC measurement, but we do have additional toroids and a resistive wall monitor for making AC measurements. Because we do keep the beam in a barrier potential well, there is a strong AC signal available (see figure 4).

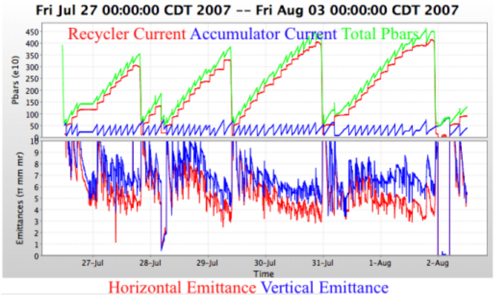

Figure 3: An operational week for the Recycler. In the top plot, blue is the Accumulator intensity, red is the Recycler intensity, and green is the sum (in units of 10^{10}. In the bottom plot, red is the horizontal transverse emittance and blue is the vertical transverse emittance (both 95% normalized π mm mrad).

By sampling and integrating the signal, we can calculate the beam intensity. We use 588 samples (the number of 53 MHz RF buckets in the Main Injector, which has the same circumference and serves as a convenient clock) over the 11.13 μsec time of a revolution. By looking for the minimum in the signal and correlating it with the time where we expect that there is no beam, we can define a baseline. However, if there are high momentum antiprotons (with $\Delta p > 18$ MeV/c), they will not be trapped within the barrier potential well and will be DC beam within the Recycler. This DC beam causes a baseline shift. As the beam is strongly cooled by the electron cooler, these free particles fall into the potential well, so the baseline moves down and the beam intensity over baseline increases, resulting in an 'increase' in the measured antiproton beam current. This behavior has made it difficult for us to truly define transfer

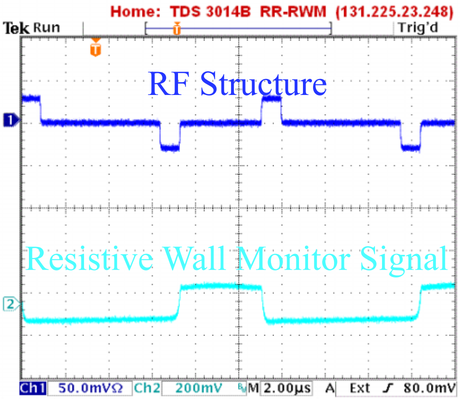

Figure 4: An oscilloscope view of the RF waveform (the integral creates a potential well) and the resistive wall monitor signal. The Recycler revolution period is 11.13 μsec, so the 20 μsec displayed shows more than 1 full turn.

efficiencies, peak intensities, beam lifetimes, or any other measures that depend upon accurate and precise measures of beam current. As all antiprotons coming in and going out travel through the Main Injector, we use the measured intensities in that machine to define some of our performance criteria.

With these caveats, the week summarized in figure 3 saw 2.72×10^{13} antiprotons transferred into the Recycler and 1.82×10^{13} transferred out of the Recycler (with loss of $\approx 1.2 \times 10^{12}$ due to the controls failure).

A standard accumulation period is approximately 25 hours. Soon after the antiprotons have been transferred from the Recycler, we accept antiprotons from the Accumulator, which has been stacking during the Recycler – Tevatron transfer process. The electron cooler is not needed until the accumulated intensity is $> 100 \times 10^{10}$, giving approximately 4 hours where beam studies can be done with the electrons without disturbing the antiprotons. Once the intensity reaches this threshold, the electron cooler is turned on with electron current of 100 mA. The electron beam is radially offset from the antiproton beam to control the cooling rate [4]. For the final hour of cooling before transfer to the Tevatron, the beam current is increased to 200 mA and slowly brought 'on–axis' with the antiproton beam. This cooling approach has been driven by the desire to control the longitudinal and transverse emittances of the antiprotons as a function of intensity so that the Tevatron can handle the antiproton beam brightness.

We have reached this operating mode by optimizing the average accumulation of antiprotons (which includes stacking performance in the Accumulator, the transfer time, and efficiency from the Accumulator to the Recycler) balanced against the integrated luminosity in the Tevatron. The integrated luminosity in the Tevatron is a complicated mix of beam intensities, emittances, and tune operating point [10], with both proton and antiproton beam brightness important inputs to the performance.

COLLIDER PERFORMANCE

The goal of the Recycler is to provide bright antiproton beams to the Tevatron Collider, to maximize the integrated luminosity for the two collider experiments. History has shown that antiproton intensity is the single strongest correlation for the collider program. Figure 5 shows the number of antiprotons (in units of 10^{10}) available at the start of a Tevatron shot. The horizontal axis is time, with the different colors representing different fiscal years (as defined by the US government, which differ from calendar years in that they go from 1 October to 30 September). The first 3 years (to the start of 2005), we only had the Accumulator available as an antiproton storage ring. Starting in 2005, we used both the Accumulator and the Recycler. During this period, the Recycler was limited to intensities of $< 175 \times 10^{10}$ because of limitations in the stochastic cooling and the lack of a transverse damper. Starting in the fall of 2005 through the present, with the commissioning of electron cooling and transverse dampers, the Recycler has become the main antiproton storage ring. The peak number of antiprotons available to the collider has doubled in the last 2 years. This doubling is a result of stacking improvements in the Accumulator [9], operational improvements in transfer time and efficiency, and the operation of electron cooling in the Recycler.

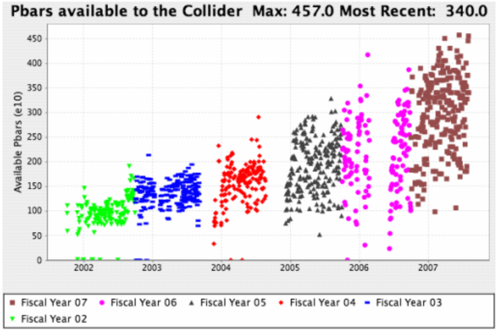

Figure 5: The number of antiprotons (by US government fiscal year) available to the Tevatron Collider. During the time period 2002-2004, antiprotons were stored only in the Accumulator. Starting in 2005, we began using both the Accumulator and the Recycler. After the commissioning of the electron cooling in the Recycler [3] in the summer and fall of 2005, the Recycler became the sole repository for antiprotons.

With the increased intensity comes the question, can the Recycler preserve the transverse and longitudinal emittance? Intrabeam scattering emittance diffusion, stochastic cooling performance, instabilities, etc., are all strongly intensity dependent. In figure 3, the lower plot shows the transverse emittances as measured for intensities ranging from $\approx 10 \times 10^{10}$ to $> 450 \times 10^{10}$. The transverse emittances are all kept within the range of $5 - 7\ \pi$ mm mrad, which is the required target for the Tevatron collider. Smaller transverse emittances can actually hurt integrated luminosity performance, because of changes to the beam and emittance lifetimes in the Tevatron due to beam beam effects [10]. In figure 6, the 95% longitudinal emittance (assuming a Gaussian beam distribution) is shown as a function of the Recycler antiproton intensity. Most stashes are between 54 and 70 eV secs, with the stated goal of 54 eV sec and available bucket area of 72 eV sec. As the electron cooled beam distribution is sharper than a Gaussian (for example, we measure an RMS of 2.66 MeV/c momentum spread and that the 90% width is 7.7 MeV/c, while for a Gaussian distribution we would expect a 90% width of 8.8 MeV/c), this measure is an overestimate of the 95% longitudinal emittance, which is why operationally we accept this measure up to 70 eV sec for transfers.

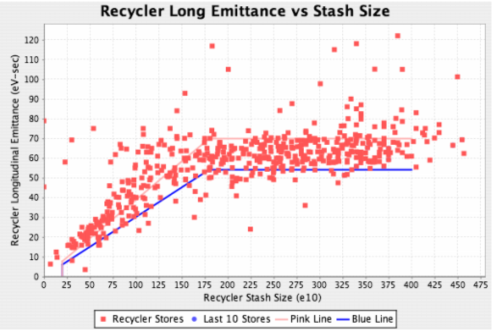

Figure 6: The calculated 95% longitudinal emittance (in units of eV-sec, assuming a Gaussian beam distribution) for the Recycler as a function of the beam intensity (units of 10^{10}). The pink and blue lines represent performance goals for cooling performance.

Figure 7 shows the peak luminosity attained in the Tevatron as a function of time. Since the Recycler and electron cooling became part of standard operations in the fall of 2005, the peak luminosity has doubled, both because of improvements in the Accumulator [9], the Tevatron [10], and the use of the Recycler and electron cooling. With continuing improvements to the Accumulator stacking performance, operational experience with the Recycler and electron cooling, and continuing work with the Tevatron, we anticipate that we will continue to push the number of antiprotons accumulated to $> 500 \times 10^{10}$ and the peak luminosity to $> 3 \times 10^{32}/\mathrm{cm}^2/\mathrm{sec}$.

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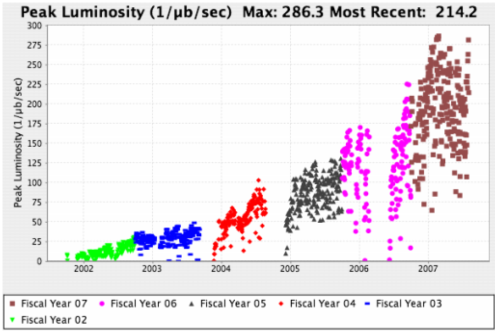

Figure 7: The peak luminosity (in units of $10^{30}/\mathrm{cm}^2/\mathrm{sec} = 1\mu\mathrm{b}^{-1}/\mathrm{sec}$) achieved in the Tevatron Collider. During the time period 2002-2004, antiprotons were stored only in the Accumulator. Starting in 2005, we began using both the Accumulator and the Recycler. After the commissioning of the electron cooling in the Recycler [3] in the summer and fall of 2005, the Recycler became the sole repository for antiprotons. There have been many improvements in the Tevatron performance to handle the higher antiproton intensities [10].

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