STATUS OF ANTIPROTON ACCUMULATION AND COOLING AT FERMILAB’S RECYCLER*

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Abstract
The Recycler ring is an 8 GeV permanent magnet storage ring where antiprotons are accumulated and prepared for Fermilab’s Tevatron Collider program. With the goal of maximizing the integrated luminosity delivered to the experiments, storing, cooling and extracting antiprotons with high efficiency has been pursued.

Over the past two years, while the average accumulation rate doubled, the Recycler continued to operate at a constant level of performance thanks to changes made to the Recycler Electron Cooler (energy stability and regulation, electron beam optics), RF manipulations and operating procedures. In particular, we discuss the current accumulation cycle in which ~400×10^10 antiprotons are accumulated and extracted to the Tevatron every ~15 hours.

INTRODUCTION
Fermilab’s Recycler was designed to provide an additional storage ring for the accumulation of 8 GeV antiprotons [1] and is now a critical component of the accelerator complex, without which the latest initial and integrated luminosity records for a hadron collider would not have been possible. The Recycler receives antiprotons from the Accumulator ring, and, through the combined use of stochastic [2] and electron cooling [3], stores up to 500×10^10 particles, which are then extracted to the Tevatron collider. Over the past two years, the average antiproton accumulation rate more than doubled, imposing more stringent requirements for cooling and storing in the Recycler.

In this paper we characterize the Recycler performance by considering its ability to maintain the proper throughput of antiprotons in order to optimize the use of the whole accelerator chain, its efficiency storing the antiprotons, and the parameters of the bunches to be extracted to the Tevatron. In particular, we discuss the Recycler Electron Cooler (REC) [4] most recent improvements as well as modifications of the RF manipulations and procedures developed to limit losses.

RECYCLER PERFORMANCE
Accumulation & Cooling Scenario
At Fermilab, antiprotons are produced by striking an Inconel target with 120 GeV protons coming out of the Main Injector every 2.2 s. 8 GeV antiprotons are collected in the Debuncher ring where they are cooled stochastically and then transferred to the Accumulator ring. The rate at which antiprotons are accumulated in the Accumulator is referred to as the stacking rate.

Table 1 summarizes side by side the different running conditions between the summer of 2007 [5,6] and the summer of 2009. Antiprotons are transferred to the Recycler every 30 minutes in sets of two ‘parcels’ instead of 3 or 4 ‘parcels’ every 2-3 hours two years ago. The transfer efficiency was kept >95%. In turns, the optimum collider store duration was found to be ~15 hours, during which a ‘stash’ (i.e. number of antiprotons stored in the Recycler as opposed to the ‘stack’ that refers to the Accumulator) of ~400×10^10 antiprotons is built for extraction to the Tevatron [7].

Table 1: Summary of the Main Antiproton Production Parameters in the Summers of 2007 and 2009

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Summer ’07</th>
<th>Summer ’09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average stacking rate, ×10^10 antiprotons per hour</td>
<td>19</td>
<td>26</td>
</tr>
<tr>
<td>Stack size for transfers</td>
<td>45-50×10^10</td>
<td>25-30×10^10</td>
</tr>
<tr>
<td>Frequency of transfers, hr</td>
<td>2-3</td>
<td>0.5</td>
</tr>
<tr>
<td>Average stash size</td>
<td>~300×10^10</td>
<td>~400×10^10</td>
</tr>
<tr>
<td>Collider store duration, hr</td>
<td>~25</td>
<td>~15</td>
</tr>
</tbody>
</table>

Figure 1 shows a comparison of the evolution of the number of antiprotons as well as the rms momentum spread during typical accumulation sequences in the Recycler in June 2007 and May 2009. It illustrates the move from larger transfers at large intervals to smaller transfers more often.

After the last transfer from the Accumulator, the longitudinal emittance is reduced to 60-70 eV s (95%) and 94-96% of the beam is ‘mined’. Mining is the RF manipulation which takes the stored antiprotons from a single 6.1 μs-long bunch to 9 macro-bunches captured in mini barrier buckets while leaving high momentum particles in the so-called ‘hot bucket’ [8]. From there, each macro-bunch is successively divided into four 2.5 MHz bunches, which are then extracted to the Main Injector with >98% efficiency and from the Main Injector to the Tevatron for collisions. Note that the time between the last transfer from the Accumulator and extraction to the Tevatron was also diminished considerably as it currently lasts 1-1.5 hours, while 2-2.5 hours were typical 2 years ago.

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04 Electron Cooling
Figure 1: Typical accumulation and cooling cycle in the Recycler in Jun 2007 (green curves) and May 2009 (blue curves). Solid lines: number of antiprotons. Lines with circle or square data points: rms momentum spread. Note that the upward slopes between transfers for the 2007 data are due to the Recycler DCCT not working properly, and is not real.

Storage Efficiency

During both injections and extractions, the antiprotons travel through the Main Injector. By comparing the number of particles that come through during injections and extractions, we have a measure of the efficiency of the Recycler as a repository of antiprotons. Numerically, the storage efficiency is defined as

\[
\frac{N_p \text{ extracted to MI} - N_p' \text{ left in RR}}{N_p \text{ transferred from MI to RR} + N_p' \text{ left from previous extraction}} \tag{1}
\]

where \(N_p\) is the number of antiprotons measured by the Main Injector DC Current Transformer (DCCT) and \(N_p'\) is the number of antiprotons measured by the Recycler DCCT. Thus calculated, the storage efficiency includes injection and extraction efficiencies from and to the Main Injector, losses due to the antiprotons lifetime and accidental losses (e.g.: correctors’ power supply trip, vacuum burst, and instability). A normal storage efficiency, where there is no accidental loss or operational issue, is ~93%. Out of the 7% of beam which is lost, ~3.5% is due to injection and extraction inefficiencies. The other ~3.5% comes from the antiprotons lifetime.

Figure 2 shows the evolution of the number of antiprotons and the associated beam loss between subsequent firing of a kicker for an accumulation and cooling cycle with typical storage efficiency. Note that the losses increase as a function of the number of stored antiprotons. Because of this, all cooling procedures were optimized in priority for when the number of antiprotons in the Recycler is large.

Figure 2: Beam intensity measured after a transfer (blue diamonds) and beam loss (pink squares) between injections/extractions during one cycle of accumulation. April 20 -21, 2009. Upper points on the loss curve correspond to time between two – parcel transfers, and the lower points are the loss between parcels. The life time drops with intensity from ~ 700 hrs to ~150 hrs.

Cooling Efficiency

In addition to storing antiprotons as efficiently as possible, the Recycler has to deliver the beam with adequate phase-space characteristics from larger average stash sizes and less time for cooling.

In practice, the fraction of the beam to be extracted from the stash (so-called mining efficiency) is determined by its longitudinal emittance during the mining process. Under normal conditions, the amount of beam which is extracted to the Main Injector reaches a near maximum of 95-96% for a longitudinal emittance of 65 eVs (95%), which is our nominal target emittance at this time. For fairly low numbers of antiprotons (<200×10^{10}), mining efficiencies as high as 98-99% can be reached. Further decrease of the longitudinal emittance is limited by instabilities and poor lifetime.

Once the beam is mined and the 2.5 MHz bunches formed, the beam is cooled further and typically reached an equilibrium emittance of 1.0 eV s per bunch (95%, average of all bunches) and 2 π mm mrad (95%, normalized, flying wires). For a given RF structure, the final emittances depend weakly on the pre-history of beam or the number of particles (Figure 3) but this equilibrium is a good indication that the strength of the electron cooling force is not deteriorating. In addition, note that for these parameters, the intra beam scattering (IBS) makes the distribution of average velocities in the beam frame “spherical”, i.e. \(\langle v_i\rangle = \langle v_p\rangle = \langle v_f\rangle\). Consequently, emittances can only be decreased together for a given RF structure.
Figure 3: Average transverse emittances (flying wire, 95%, normalized) of the last 4 extracted bunches as a function of the stash size. Green triangles: June 2006-August 2007 data; Blue diamonds: November 2007-June 2009 data.

Contribution of stochastic cooling

While the increased frequency of transfers from the Accumulator and the larger average number of antiprotons stored in the Recycler are not favorable for stochastic cooling and diminish its overall efficiency, its role cannot be ignored for achieving high storage efficiencies.

First, after most of the beam has been extracted to the Tevatron, the Recycler is left with a fairly low number of particles (10-30×10¹⁰) with large transverse emittance and momentum spread. In these conditions, the cooling efficiency of the electron beam is greatly diminished and the stochastic cooling system is essential for preparing the bunch to accept the first set of transfers from the Accumulator in a timely manner.

Most importantly, while the stochastic cooling rate decreases rapidly as the number of stored antiprotons increases (as ~1/N) and stochastic cooling is not needed to achieve the beam parameters required for extraction to the Tevatron, we found that it was important to keep it on, even with very little output power, in order to maintain decent lifetime at large stash sizes.

**MAIN IMPROVEMENTS**

**Electron Cooling Optimization**

Two major contributions to the effectiveness of electron cooling are the electron beam energy stability and the electron beam angles (i.e. rms transverse velocities over the length of the cooling section).

As already noted in Ref. [6], we found that the electron beam energy was drifting and we described how we use a large dispersion area in our beam line to provide a real-time beam-based measurement of the energy drift or relative error. This energy error is now used in a stand-alone software application, which makes the necessary adjustments to the Pelletron charging system in order to keep the electron beam energy to within 500 V of its nominal [9]. In parallel, a lot of attention has been paid to the temperature control of the Pelletron and the Generating Voltmeter (GVM), the instrument used to measure the terminal high voltage, because of their clear influence on the energy (true or measured). In steady state, the SF₆ cooling system keeps the Pelletron temperature within ±0.2 K. Because a large portion of the heat load is removed from the Pelletron tank through its walls, the ambient temperature affects the cooling efficiency of the tank and thus the voltage stability. Presently, three air conditioning units keep the temperature in the building within ±1 K. Finally, a thermal regulator was installed with the GVM, and now its temperature varies typically by ±0.5 K over several weeks, effectively eliminating this source of the energy drift [9].

One contribution to the total angles in the electron beam arises from deviations of the beam envelope from cylindrical in the cooling section. Such distortions can be studied by imaging the beam in the pulse mode on a removable scintillator (YAG crystal [10]) located at the exit of the cooling section and captured by a gated CID camera [11].

Dedicated measurements carried out in 2007 showed a large contribution from quadrupole oscillations in the cooling section, confirming the preliminary results of Ref. [6]. With a special procedure, the electron beam transverse distribution was brought closer to an ideal axially symmetrical shape using 6 upstream quadrupoles [12]. However, cooling rates with a DC beam did not improve. Qualitatively, a possible explanation for this result may be that, in DC mode, secondary ions, which accumulate in the beam potential, lead to a significantly different envelope than for the pulsed beam. Nevertheless, similarly to what was done in the pulsed mode with the YAG but using drag rate measurements instead of beam images, the quadrupoles were tuned with a DC beam and lead to higher cooling rates both longitudinally and transversely. In particular, for an electron beam offset of 2 mm with respect to the antiproton trajectories, the cooling rate increased by 1.5-2 times [12, Fig. 4].

The electron beam angles also deteriorate with time because of the tunnel ground motion that affects the relative position of the cooling solenoids with respect to one another, thus inducing dipole kicks along the cooling section [13]. To correct, a procedure based on drag rate or cooling rate measurements was developed and is described in Ref. [13]. Although the uncertainties of this procedure are large, it successfully improved the cooling efficiency in operation. At this time, we find that it needs to be repeated every ~6 months to avoid a noticeable deterioration of the cooling rate.

Finally, while in theory the cooling force should increase with the electron beam current, in our experience, the maximum drag/cooling rates were found at 100 mA, our present operating beam current. We do not have a satisfying explanation for this limitation at this time.

**Cooling Procedures & RF Manipulations**

The basic procedures for accumulating and cooling antiprotons in the Recycler have not changed and are
described in Refs [5,6,8]. They heavily rely on the REC, its performance, and its availability. However, the improvements highlighted above allowed for some operational simplifications without impairing the cooling and storage efficiencies. In addition, a RF manipulation during injections was revisited with beneficial results.

Because the portion of the time when the electron beam is not needed became relatively small (~15%), the electron beam is now on at all times. By leaving the electron beam on, the REC gained in stability, notably the electron beam energy. Then, instead of constantly moving the electron beam to adjust the cooling rate, we leave the electron beam at a constant position, namely 2 mm offset (vertically) from the antiprotons central orbit. With the improved cooling rate, we found that this position was adequate to cool all stashes up to the record number of \(525 \times 10^{10}\) antiprotons. While the optics solution with quadrupoles improved the cooling efficiency, the antiprotons lifetime still deteriorates when the cooling rate increases \((i.e.\) when the electron beam is moved closer to the antiprotons central orbit). Thus keeping the electron beam at a constant offset might slightly deteriorate the antiprotons lifetime at low intensities \((<150 \times 10^{10})\). On the other hand, Figure 2 shows that the impact on the total beam loss is small because the total beam loss is mostly determined by the lifetime at high intensities where cooling cannot be traded for lifetime preservation.

The new cooling procedure also reduces the number of manipulations of the electron beam, which in turns limit the risk of overcooling the antiproton beam because of an operational mistake. Note that Operators still have the possibility of moving the electron beam in non-standard situations.

An important improvement for increasing the storage efficiency was the slight modification of the RF manipulations during the injection process. Just before injections, the potential well is deepened in order to capture as many DC particles \((i.e.\) particles not contained by the RF bucket) as possible to avoid their loss when the injection kicker fires. Analyses found that this manipulation was done too rapidly for adiabatic capture, and it was slowed down. Figure 4 shows the transfer efficiency before and after the RF modification. On average, the transfer efficiency increased by 3% (thus increasing the storage efficiency). In particular, the modified RF manipulation significantly reduced the sensitivity of the transfer efficiency on the number of stored antiprotons.

### RESISTIVE WALL INSTABILITY

One of the limitations on the Recycler beam’s brightness is a resistive wall instability [14,15]. To first order, its threshold is determined by the ‘phase density’ of the bunch, which, we defined as:

\[
D = \frac{N_P}{4 \epsilon_{L_{rms}} \epsilon_T}
\]

(2)

where \(N_P\) is the number of antiprotons in units of \(10^{10}\), \(\epsilon_{L_{rms}}\) is the root-mean-square longitudinal emittance in eV s and \(\epsilon_T\) is the 95%, normalized transverse emittance in μrad. For the Recycler, a calculation of the phase density threshold for a Gaussian distribution gives 0.8 at the lowest sideband, and it was verified experimentally to within the uncertainties associated with the measurements.

This instability was dealt with by installing a transverse digital damper system in 2005 [16]. To address the increased brightness of the beam in the Recycler, the original system was upgraded, and the operational bandwidth increased from 30 MHz to 70 MHz [17,18]. Currently, we find that the beam remains stable up to \(D \sim 3.5\), in line with expectations.

Recently, we only experienced instabilities once the antiproton beam had been mined. At this stage, lifetime preservation is no longer the main consideration, and the electron beam is moved closer to the axis of the antiproton beam, providing stronger cooling, thus increasing the brightness of the antiprotons further. Interestingly, only one of the macro-bunches goes unstable at a time, although we can have several instabilities in a row affecting different macro-bunches. By looking at the dampers pickups at the onset of the instability, we see that, as expected, it is always the tail of the bunch which starts oscillating at a frequency of ~70-100 MHz, above the dampers limit (Figure 5).

![Figure 4: Transfer efficiency as a function of the transfer number. The RF change was made on June 9th, 2008 (transfer #8267). Note that the benefits from the RF modification may not be apparent right away because of the accelerator chain conditions and destructive studies taking place concurrently.](image)
Figure 5: Example of an instability during extraction affecting a single macro-bunch. The black curve is the kicker response. The red and blue curves are the pickups signals. The green trace is the intensity profile.

All the latest instability events developed when the antiproton beam was cooled for several hours without injections before final cooling and tuning. This may indicate a correlation with better cooling of the tails particles, thus diminishing the number of resonant particles (‘Landau particles’) that help maintain beam stability. Calculation of the instability threshold for the value of $D$, Eq. (2), for a Gaussian and a step-like distribution finds that it is $\sim 2$ times higher for the Gaussian distribution than for the step-like distribution [19]. Unfortunately, in operation, there is no measurement that can resolve quantitatively the amount of tail particles (at the level of $\sim 0.0001$) so that we could predict (and avoid) the instability to occur. We do however recognize that the lifetime gives a good indication of whether or not we might be near the instability threshold. Typically, this would be the case if the lifetime is greater than 500 hours for a stash of $>350 \times 10^9$.

While increasing the dampers bandwidth by a factor of 2 was entirely done through improving the electronics, going further would require hardware modifications in the vacuum chamber (kickers and/or pickups). There are no such plans for the remaining of the Tevatron running period.

CONCLUSION

Over the past two years, the average antiproton flux in the Recycler more than doubled. Nevertheless, the Recycler was able to accommodate these higher rates with the same efficiency as before. This was achieved merely through fine tuning of existing components and procedures in a context where only percent level improvements could be expected.

A better control of the REC electron beam envelope as well as of its energy, along with slightly modified RF manipulations permitted to streamline and simplify the cooling and accumulation procedures, making the operation of the Recycler more robust.

ACKNOWLEDGMENTS

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REFERENCES

[10] Use of YAG for beam imaging in the cooler was proposed by W. Gai, and the crystal was provided by his ANU group.