1.1 Fermilab's 4.3-MeV Electron Cooler

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1.1.1 Introduction

The antiproton source for a proton-antiproton collider at Fermilab was proposed in 1976 [1]. The proposal argued that the requisite luminosity (~10^{29} $cm^{-2}s^{-1}$) could be achieved with a facility that would produce and cool approximately 10^{11} antiprotons per day. At the end of its operation in 2011, the Fermilab antiproton production complex consisted of a sophisticated target system, three 8-GeV storage rings (namely the Debuncher, Accumulator and Recycler), 25 independent multi-GHz stochastic cooling systems and the world's only relativistic electron cooling system. Sustained accumulation of antiprotons was possible at the rate of greater than 2.5×10^{11} per hour.

The production of antiprotons started with a 120 GeV proton beam from the Main Injector striking an Inconel target every 2-3 seconds. From all the particles thus created, 8.9–GeV/c antiprotons were collected in the Debuncher and stored in the Accumulator (the process known as stacking). The Recycler [2] is a permanent-magnet, fixed momentum (8.9 GeV/c) storage ring located in the Main Injector tunnel. As conceived, the Recycler would provide storage for very large numbers of antiprotons (up to 6×10^{12}) and would increase the effective production rate by recapturing unused antiprotons at the end of collider stores (hence the name Recycler). Recycling of antiprotons was determined to be ineffective and was never implemented. However, the Recycler was used as a final antiproton cooling and storage ring. The Accumulator antiproton stack was periodically transferred to the Recycler where electron cooling allowed for a much larger antiproton intensity to be accumulated with smaller emittances. Typically 22-25×10^{10} antiprotons were transferred to the Recycler every ~60 minutes. Prior to electron cooling in the Recycler, antiprotons destined for the Tevatron were extracted from the Accumulator only. Since late 2005, all Tevatron antiprotons were extracted from the Recycler only. Figure 1 illustrates the flow of antiprotons between the Accumulator, Recycler and Tevatron over a one-week period.

The Recycler had a number of stochastic cooling systems in operation from day one; the electron cooling system was envisioned as an upgrade [2] to complement the stochastic cooling system (in particular the longitudinal one because of the longitudinal injection scheme in the Recycler) and was placed into operation within days of its first successful demonstration in July 2005 [3]. Electron cooling in the Recycler directly allowed for significant improvements in Tevatron luminosity. With it, the Recycler has been able to store up to 6×10^{12} antiprotons. In routine operations, the Recycler accumulated 3.5-4.0×10^{12} antiprotons with a ~200-hr lifetime before injection into the Tevatron [4].

In this paper we will describe the electron cooling system installed in the Recycler, its physics principles, and the electron cooling measurements.

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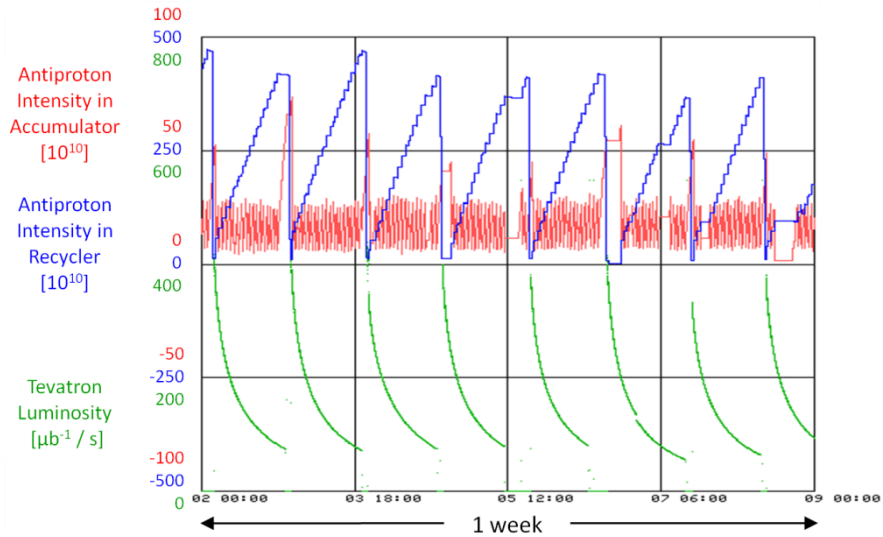

Figure 1: Production and transfers of antiprotons between the Accumulator and Recycler over a period of one week. While the Tevatron had a colliding beam store, small stacks of antiprotons were produced and stored in the Accumulator, and then periodically transferred to the Recycler in preparation for the subsequent Tevatron fill.

1.1.2 Recycler Electron Cooling (REC) System

Electron cooling is a method of increasing the phase-space density of "hot" heavy charged particles, ions or antiprotons, through Coulomb interactions with a "cold" electron beam, co-propagating with the same average speed in a small section of the ring. The method was proposed by G. Budker in 1967 [5], successfully tested in 1974 with low-energy protons [6], and later implemented at a dozen of storage rings (see, for example, a review [7]) at non-relativistic electron energies, E_e <300 keV.

Figure 2 shows the schematic layout of the Fermilab electron cooling system. The Pelletron (an electrostatic accelerator manufactured by the National Electrostatics Corp.) provided a 4.3 MeV (kinetic) electron beam (up to 500 mA, DC) which overlapped the 8-GeV antiprotons circulating in the Recycler in a 20-m long section and cooled the antiprotons both transversely and longitudinally. The dc electron beam was generated by a thermionic gun, located in the high-voltage terminal of the electrostatic accelerator. This accelerator was incapable of sustaining dc beam currents to ground in excess of about 100 μA. Hence, to attain the electron dc current of 500 mA, a recirculation scheme was employed, in which the electron beam that has interacted with the antiprotons is decelerated to 3.5 keV and accepted into the collector, located in the high-voltage terminal of the Pelletron The typical relative beam current loss in the system was 2×10^{-5} [8].

The Fermilab cooler employed a unique beam transport scheme [9]. The electron gun was immersed in a solenoidal magnetic field, which created a beam with large angular momentum. After the beam was extracted from the magnetic field and accelerated to 4.3 MeV, it was transported to the 20-m long cooling section solenoid using lumped focusing elements (as opposed to low-energy electron coolers where the beam remains immersed in a strong magnetic field at all times). The cooling section solenoid removed this angular momentum, and the beam was made round and parallel such that the beam radius, a, resulted in the same magnetic flux, Ba^2, as at the cathode.

The magnetic field in the cooling section was low, ~100 G, therefore the kinetics of the electron-antiproton scattering was weakly affected by the magnetic field.

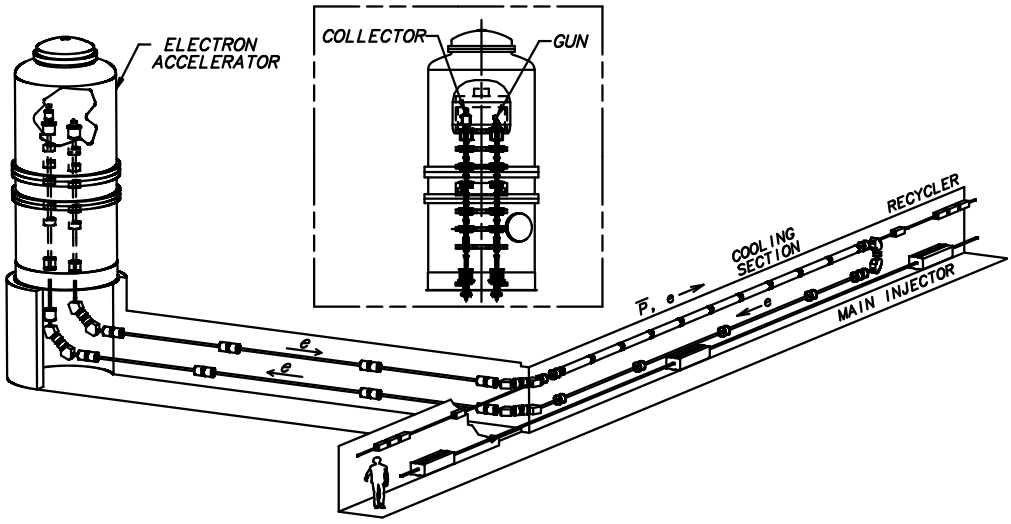

Figure 2: Schematic layout of the Recycler electron cooling system and the accelerator cross-section (inset).

1.1.3 Electron Cooling Formulae

A heavy charged particle moving in a free electron gas with a velocity distribution $f_e\left(\overrightarrow{v_e}\right)$ experiences a friction force that in a model of binary collisions can be written following Ref. [6]:

$$\overrightarrow{F_b}\left(\overrightarrow{V_p}\right) = -\frac{4\pi e^4 n_{eb}}{m_e}\eta\int L_C \frac{f_e(\overrightarrow{v_e})}{(\overrightarrow{V_p}-\overrightarrow{v_e})^2}\frac{\overrightarrow{V_p}-\overrightarrow{v_e}}{\left|\overrightarrow{V_p}-\overrightarrow{v_e}\right|}d^3v_e\,, \qquad (1)$$

where n_{eb} is the electron density in the beam rest frame, m_e the electron mass, e the elementary charge, $\overrightarrow{V_p}$ the velocity of the heavy particle, and $\eta = L_{cs}/C$ indicates the portion of the ring circumference C occupied by the cooling section of length L_{cs}. L_C is the Coulomb logarithm

$$L_C = \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right). \qquad (2)$$

with the minimum and maximum impact parameters, $\rho_{\min}$ and $\rho_{\max}$, in the Coulomb logarithm defined as

$$\rho_{\min} = \frac{e^2}{m_e(\overrightarrow{V_p}-\overrightarrow{v_e})^2},\ \rho_{\max} = \min\left\{R_D, R_e, \left|\overrightarrow{V_p}-\overrightarrow{v_e}\right|\cdot\tau_f\right\}. \qquad (3)$$

The maximum impact parameter is determined by the electron beam radius R_e, (typically the case in the Fermilab cooler), the Debye radius R_D, or the relative displacement of the particles during the flight time through the cooling section $\tau_f = \frac{L_{cs}}{\gamma\beta c}$, where γ and β are the relativistic factors of co-propagating particles in the lab

frame, whichever is the smallest. In this paper, the electron velocity distribution is assumed to be Gaussian in each plane. Note that if the variations of the Coulomb logarithm in the integrand of Eq. (1) can be neglected, L_C can be taken out of the integral and instantaneous cooling rates of an antiproton beam with a Gaussian velocity distribution can be expressed with elementary functions [8].

1.1.4 Cooling measurements

Analysis of the cooling properties of the electron beam was made primarily with 'drag rate' measurements obtained via a voltage jump method similar to the one used in the early age of electron cooling [10]: a "pencil" coasting antiproton beam is cooled to an equilibrium; then, the electron energy is changed by a jump, and the rate of change of the mean value of the antiprotons momentum distribution is recorded while the antiprotons are dragged toward the new equilibrium. If the momentum spread remains small in comparison with the difference between the two equilibriums, this '*drag* rate' is equal to the longitudinal *cooling* force. Results of the drag force as a function of the voltage jump amplitude (expressed in units of the antiproton momentum offset) are presented in Fig. 3. For these data, the electron and antiproton beams are concentric and collinear, which was defined as the electron beam being 'on-axis'.

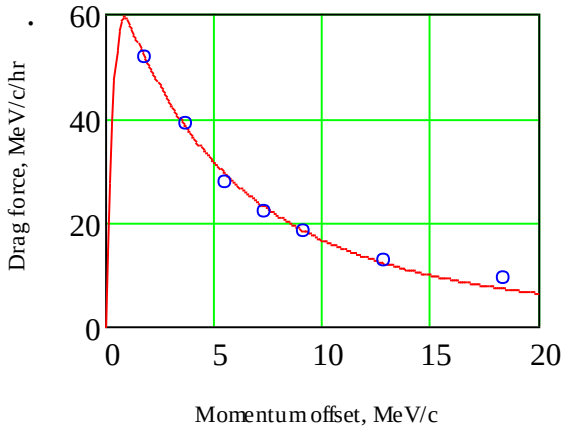

Figure 3: Drag rate on-axis as a function of momentum offset. Electron beam current I_e = 0.1A. The circles are data, and the solid line is a calculation using Eq.(1) with the rms electron angle of θ_e= 80μrad and energy spread of δW_e= 200eV, L_c= 9.

For the case of the Fermilab cooler, the main contribution to the cooling force comes from collisions with low impact parameters. Therefore, the drag rate depends primarily on the electron beam properties in the vicinity of the probing antiproton beam. In turn, information about the transverse distribution of the electron density and angles can be obtained with drag rate data taken at several spatial offsets (parallel shifts) between the two beams in the cooling section. Fig. 4 shows an example of such measurements along with a fit to a simplified formulation of the drag rate as a function of the transverse distance between the two beams (or equivalently, the radius of the electron beam) written as

$$F_{lz}(x) = F_0\left(\Delta p_p\right)\cdot\begin{cases}\dfrac{1-\left(\dfrac{x}{a_e}\right)^2}{1+\left(\dfrac{x}{b}\right)^2}, x \le a_e \\ 0,\ x > a_e\end{cases}, \tag{4}$$

where a_e is the electron beam radius and F_0, the maximum drag rate (by definition at the center of the electron beam current density transverse distribution) for a given momentum offset. In the fraction, the numerator approximates the electron current density profile determined from electron gun simulations, while in the denominator, b describes an increase of the electron angles with the radial offset. For such a profile, the finite size of the probe antiproton beam results in a decrease of the measured drag rate in comparison with the cooling force experienced by the antiprotons at the center. The red curve on Figure 4 shows the corresponding correction.

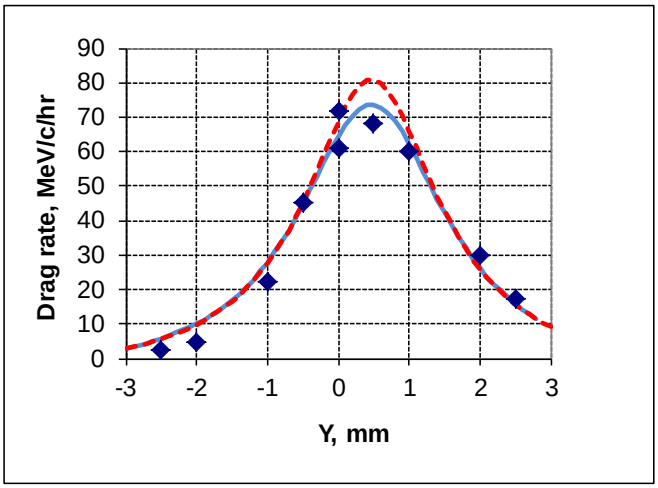

Figure 4: Drag rate as a function of the electron beam offset with respect to the co-propagating antiprotons. The voltage jump was 2 kV, $I_e = 0.3$ A, number of antiprotons $N_p = 1.3\cdot10^{10}$. The blue curve is the best fit to the model described with a_e = 4.3 mm, and fitting parameters F_0 = 80 MeV/c/hr and b= 1.2 mm. During the measurement, the rms size of the antiproton beam was estimated to be ~0.25 mm. The red dashed curve shows the fitted cooling force after correcting for the finite size of the antiproton beam.

If the electron angles remain the same, the cooling force should increase proportionally to the current density. Drag rates measured at different beam currents during the entire span of the cooler's operation are shown in Fig. 5 together with the simulated current density at the beam center.

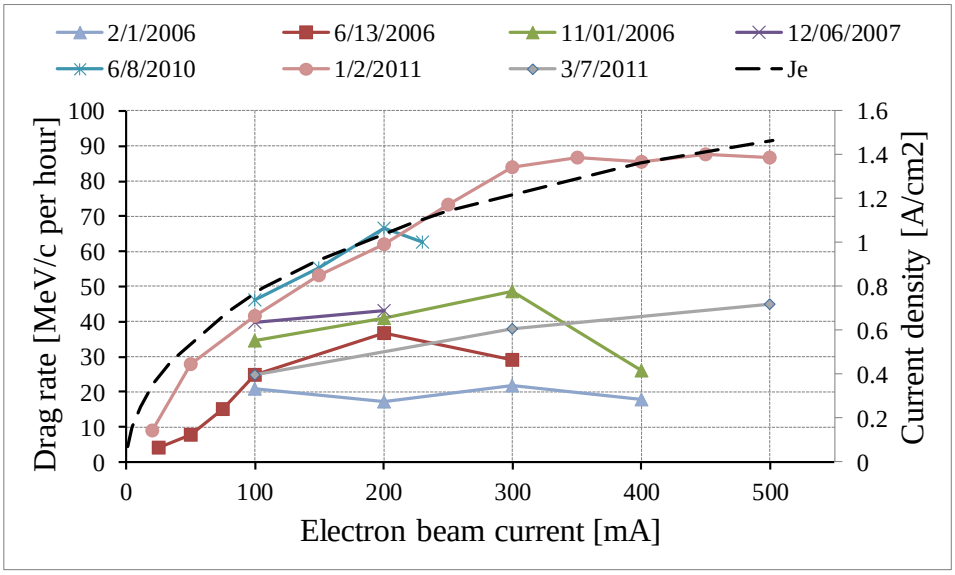

Figure 5: Drag rate measured on axis as a function of the beam current at various dates with a 2 kV voltage jump. The current density calculated at the beam center (dashed curve) is shown for comparison.

The large scatter in the measured drag rates is related to important variations of the electron angles in the cooling section. Until the end of the collider operation, significant efforts were devoted to understanding what determined these angles and how they could be reduced. Best estimates of the various contributions to the total rms electron angle are presented in Table 1.

Table 1: Contributions to the total electron angle in the cooling section. Shown values are 1D, rms, obtained from averaging the angles over the cross section of a 0.1A beam in the best scenario.

Effect	***Angle, μrad***	***Method of evaluation***
Thermal velocities	57	Calculated from the cathode temperature
Envelope mismatch	~50	Resolution of tuning + optics simulations
Dipole motion (above 0.1 Hz)	~35	Spectra of BPMs in the cooling section
Dipole motion caused by field imperfections	~50	Simulation of electron trajectory in the measured magnetic field
Non-linearity of lenses	~20	Trajectory response measurements
Ion background	< 10	Cooling measurements
Total	~100	Summed in quadratures

With a detailed description of improvements and measurements given in Ref. [8], here we would like only to highlight several important milestones in the evolution of the electron beam angles:

- Quadrupole correctors allowed to significantly decrease the beam envelope angles at low beam currents.
- Development of a beam-based procedure for aligning the magnetic field in the cooling section alleviated the effect of mechanical drifts of the cooling section's solenoids.

- Clearing the background ions to <1% of the electron density by interrupting the electron beam for 2 μs at 100 Hz improved cooling at higher beam currents.

While the drag rate measurements were the instrument to estimate and improve the electron beam properties, cooling efficiency for operation was described by the cooling rates. To measure cooling rates, the antiproton beam, confined by rectangular RF barriers, was first let diffuse for 15 minutes with no cooling (including stochastic cooling) and then the electron beam was turned on and cooled the antiprotons for 15 minutes. The cooling rate was calculated as the difference between the time derivatives of the momentum spread (or transverse emittances) before and after turning on the electron beam.

Typically, in this case the rms antiproton beam radius exceeded the size of the electron beam area with good cooling properties, and a model of cooling in an infinite homogenous electron gas predicted much higher cooling rates than were actually measured. One still can examine consistency between drag rates and cooling rates in a simple model assuming that measurements of the drag rates at various electron beam offsets (e.g. as in Fig. 4) represent the cooling force experienced by an antiproton at that given radius. Results of such comparisons are shown in Fig. 5, where cooling rates measured with similar electron beam conditions are plotted for different initial antiproton beam transverse emittances. The dash-dotted curve is the result of the integration of the cooling force, reconstructed from drag rate measurements for the same electron beam parameters at various offsets over a Gaussian spatial distribution of antiprotons with the rms size calculated from their measured emittance. Note that integration does not involve any additional fitting parameters. Taking into account the approximate nature of this model, the agreement is reasonable.

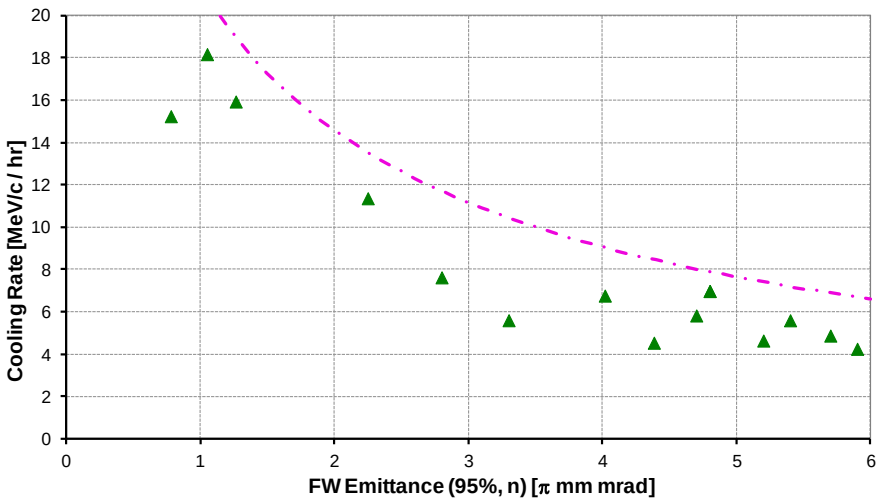

Figure 5. Longitudinal cooling rate (negated) as a function of the antiproton emittance for I_e = 0.1 A.

1.1.5 Conclusion

The Recycler Electron Cooler at Fermilab made an important contribution to the success of the Tevatron Run II by increasing the antiproton flux and brightness. It also marked a significant step in the development of accelerator technology and accelerator

physics, demonstrating for the first time relativistic cooling as well as beam transport of a magnetized beam with lumped focusing.

Drag rate measurements proved to be the main tool for analyzing and improving cooling properties of the electron beam. Various types of cooling measurements were eventually found to be mutually consistent and in a reasonable agreement with a non-magnetized description of electron cooling.

1.1.6 Acknowledgement

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1.1.7 References

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