Abstract

Antiprotons in Fermilab’s Recycler ring are cooled by a 4.3 MeV, 0.1A DC electron beam (as well as by a stochastic cooling system). The paper describes electron cooling improvements recently implemented: adjustments of electron beam line quadrupoles to decrease the electron angles in the cooling section and better stabilization and control of the electron energy.

INTRODUCTION

Since the first cooling in 2005 [1], the Recycler Electron Cooler (REC) is used for storing and preparing antiproton bunches for every Tevatron store. The cooler is based on the electrostatic accelerator, Pelletron [2] working in the energy recovery mode. The DC beam is accelerated in an acceleration tube, is delivered to the cooling section, and then returned to the HV terminal through another Pelletron’s tube (Fig. 1).

Operationally, two parameters are important for quality of electron cooling. The first one is the rms electron transverse velocity spread $\sigma_e$ in the cooling section (CS). The section is immersed into a longitudinal magnetic field, but in contrast to other existing coolers [3], the field strength, 105 G, is too low to significantly modify the cooling process. For this case of non-magnetized cooling [4], in practically interesting regimes the cooling force is proportional to $\sigma_e^{-2}$. The second crucial parameter is the energy mismatch between electrons and antiprotons. Antiproton energy in the permanent-magnet Recycler ring is very stable, while the electron energy is determined mainly by the potential of the Pelletron terminal. If this potential deviates from its optimum value by more than ~0.5 kV, the cooling rate drops, and the phase density of the antiproton beam core degrades. Efforts to decrease the transverse velocities and to stabilize the terminal potential are described below.

Optimization of transverse velocities

Electron transverse velocities (or angles) in the cooling section are determined by several effects ([5], [6]), but the subject of this section is the contribution due to focusing errors. To minimize the angles, the beam line between the cathode and the cooling section needs to provide a rotationally invariant transformation with matched magnetic fluxes [7]. However, each of the two 90 degree bends upstream of the cooling section consists of two zero-gradient 45-degree bending magnets with a dispersion-suppressing solenoidal doublet in between, and these systems do not preserve the invariance. A special solution was found in [8] that provides the necessary transformation in the approximation of linear optics. However, the beam in CS is axially symmetrical with no additional angles only at specific settings of the focusing elements. Manufacturing imperfections or power supplies drifts may cause a deviation from symmetry and an increase in the angles.

* FNAL is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
* shemyakin@fnal.gov
upstream of the cooling section (labeled SPB01 and SPB02 in Fig.1b). This tuning proved to be sufficient for demonstrating the electron cooling and successfully applying it for a dramatic improvement in cooling of antiprotons in the Recycler [1]. On the other hand, over the years indications were mounting that the angles of off-axis electrons are significantly higher than the angles on axis. The latter, estimated from drag rate measurements [10] to be ~0.1 mrad [11], was fed into BETACOOL [12] simulations of cooling rates, when the sizes of both beams are comparable. The simulated rates significantly exceeded the measured ones, and the discrepancy could be mitigated only by introducing into the model a large radial gradient of angles, ~0.3 mrad/mm [11]. To check whether the angles are created by focusing errors, a dedicated set of beam imaging measurements was performed with a removable scintillator, YAG crystal [13] (Fig.1b), which had been installed into the Recycler vacuum chamber downstream the 180-degree bend in 2004. When the bend is turned off, a cross section of a pulsed electron beam coming out of CS can be observed on the crystal. An unexpected complication was that radiation from the Main Injector synchrotron, mounted in the same tunnel, was damaging the camera in a matter of an hour. As a result, imaging of the electron beam in this location had to be performed in a dedicated run with the beam in the Main Injector inhibited.

![Figure 2](image)

**Figure 2.** Images of the beam at the YAG with zero (1 and 2) and adjusted (3 and 4) quadrupole currents. Images were recorded at zero current of the lens SPQ01 (1 and 3) and at 10.4 A (2 and 4). All other settings are the same for all images. Beam current was \( I_e = 0.1 \) A, the pulse duration was 2 \( \mu \)s, and the camera was gated for 100 ns at the peak of the pulse.

Recorded images showed a significant deviation of the beam shape from axially symmetrical (Fig.2). The main component, an elliptical distortion, was corrected by adjusting of 6 quadrupoles upstream the CS. For this correction, a special procedure that used the image ellipticity as a parameter to minimize, was developed [14] and applied in several steps. At each step, the changes in the ellipticity resulting from a small change of the current in each quadrupole were recorded at two currents of large off-axis angles. With that in mind, several sets of measurements were performed where the drag rates were recorded at various settings of the 6 quadrupoles. Starting with all quadrupoles at zero, their currents were changed one by one to the point where the drag rate was maximal, and then the similar scans were made for the two lenses SPB01 and SPB02 to optimize the axially symmetrical perturbation. This procedure was repeated for several times until no further growth of the drag rate was found. The resulting improvement at various offsets between centers of the electron and antiproton beams is shown in Fig.3. Note that part of the increased rates might come from a lower transverse size of “pencil” antiproton beam, which is poorly controlled during the measurements.

While somewhat disappointing, the results clearly indicated that quadrupole perturbations can be the source of large off-axis angles. With that in mind, several sets of measurements were performed where the drag rates were recorded at various settings of the 6 quadrupoles. Starting with all quadrupoles at zero, their currents were changed one by one to the point where the drag rate was maximal, and then the similar scans were made for the two lenses SPB01 and SPB02 to optimize the axially symmetrical perturbation. This procedure was repeated for several times until no further growth of the drag rate was found. The resulting improvement at various offsets between centers of the electron and antiproton beams is shown in Fig.3. Note that part of the increased rates might come from a lower transverse size of “pencil” antiproton beam, which is poorly controlled during the measurements.

Cooling rate, the most relevant parameter for operation, increased considerably as well (Fig.4). At present, the cooler always operates with the electron beam

![Figure 3](image)

**Figure 3.** Drag rate as a function of the offsets between antiproton and electron beams. The set labeled Y0 represents data recorded for vertical offsets before applying the quadrupole correction. The sets X and Y show the rates after the correction for offsets in horizontal and vertical directions, correspondingly. \( I_e = 0.1 \) A.
at an offset of 0.5 – 2 mm that provides strong enough cooling while preventing an instability due to an overcooled beam.

![Graph](image)

Figure 4. Comparison of the longitudinal cooling rates at various vertical offsets of electron beam before (set 2) and after (set 1) adjustments of quadrupoles. Antiproton beam parameters for set 1/set 2: number of antiprotons 100/6110\(^9\), beam length 5.5/4.1 µs, transverse emittance measured with a flying wire 2.6/3.8 \(\pi\) 95% normalized, rms momentum spread 3.2/3.5 MeV/c.

So far, attempts to apply a similar procedure to higher electron beam currents have not resulted in a drag rate exceeding the one measured at 0.1 A.

**Electron energy stabilization**

The requirement of equality of electron and antiproton velocities translates into tolerance to electron energy deviations of 0.01%. With RF off, the position of the peak of the equilibrium antiproton momentum distribution is the best indication of electron energy. In the routine operation, we rely first of all on HV stability based on Pelletron’s Generating Voltmeter (GVM, [15]). However, in a long run its stability was proved to be unsatisfactory. Additional diagnostics based on the electron beam position in a high-dispersion area of the beam line was developed and allowed identifying several mechanisms responsible for the energy drift [16]:

- Temperature sensitivity of the GVM preamplifier of 500 eV/K. Presently, the preamplifier temperature is stabilized within ±1 K.
- Dependence of the GVM reading on the Pelletron tank temperature at the rate of 400 eV/K. In a steady state, the tank temperature is now kept within ±0.2 K.
- The drift of the chain current or slow fluctuations of the corona current from the terminal change the terminal voltage at the rate of 100 eV/µA. This effect was alleviated by implementation of a software loop which adjusts the chain current based on the difference between the terminal voltage set point and the GVM reading.
- The GVM reading changes with the SF6 pressure at the rate of ~500 eV/psi because of the SF6 permittivity.

In addition to temperature stabilization efforts, a dedicated software loop is used to adjust the high voltage set point in accordance with the value of the energy error reconstructed from the beam trajectory. With these improvements, the long-term (months) energy stability is at the level of 0.01%.

**SUMMARY**

1. Imaging of the Fermilab cooler’s electron beam showed a significant quadrupole perturbation. The perturbation was decreased by adjusting quadrupoles upstream the cooling section that significantly increased the cooling rate.

2. Temperature stabilization and implementing a beam-based feedback energy regulation loop improved the long-term stability of electron energy to 0.01%.

**ACKNOWLEDGMENTS**

Authors are thankful to V. Lebedev for discussions and help with using his OptiM code.

**REFERENCES**

[2] Pelletrons are manufactured by the National Electrostatics Corporation, [www.pelletron.com](http://www.pelletron.com).
[13] Using of YAG for beam imaging in the cooler was proposed by W.Gai, and the crystal was provided by his ANU’s group
[14] The procedure was programmed by T.Bolshakov
[16] A. Shemyakin et al., Fermilab preprint CONF-08-425-AD