OPTIMIZATION OF ELECTRON COOLING IN THE RECYCLER *

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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 the electron beam line quadrupoles to decrease the electron angles in the cooling section and a better stabilization and control of the electron energy.

INTRODUCTION

Since the first cooling demonstration 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 an 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 is returned to the HV terminal through the other Pelletron tube (Fig.1).

Operationally, two parameters are important for efficient electron cooling. The first one is the rms electron transverse velocity spread σ_e in the cooling section (CS). In contrast to other existing coolers [3], the CS field strength, 105 G, is too low to significantly modify the cooling process, and in practically interesting regimes the cooling force is proportional to $1/\sigma_e^2$ [4]. The second crucial parameter is the energy match between electrons and antiprotons. The antiproton energy in the permanent-magnet-based 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. 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 CS are affected by several effects ([5], [6]), but the subject of this section is the contribution of 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]. While some of the beam line elements do not preserve the invariance, a special beam line design that provides the necessary transformation was found in [8] in the approximation of linear optics. However, this solution provides an axially symmetrical beam with no additional angles in the CS only for specific settings of the focusing elements. Imperfections of manufacturing or power supplies drifts may cause a deviation from symmetry thus an increase in the angles.

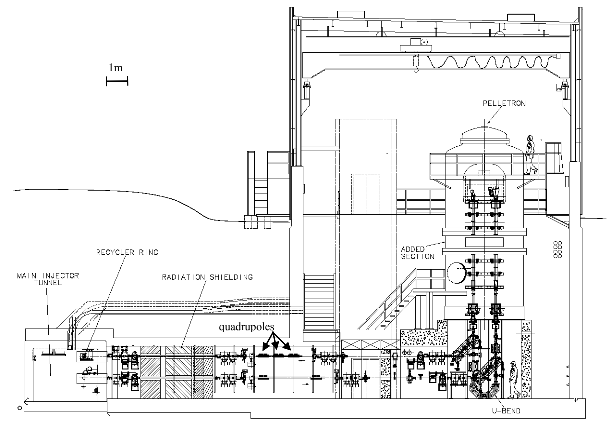

Figure 1a: Elevation view showing the Pelletron with its acceleration and deceleration tubes, the transfer lines passing through the connecting enclosure to the Recycler ring, and the cross-section of the Main Injector tunnel which houses the Recycler ring.

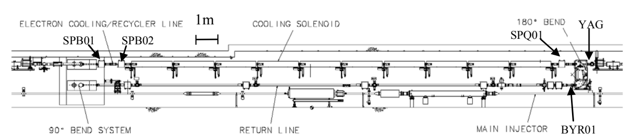

Figure 1b: Elevation view of the Main Injector tunnel showing the 90°-bend system which injects the electron beam from the transfer line into the Recycler ring, the cooling section of Recycler, the 180°-bend system which extracts the electron beam from the Recycler, and the return line. BYR01 labels the BPM in a high-dispersion location, which is used for energy measurements and stabilization.

The original plan for commissioning the beam line was to examine all the elements by measuring the responses of the electron trajectory to kicks by dipole correctors, adjust correspondingly the normalization coefficients of the focusing elements, tune the line according to the model, and verify that the resulting beam envelope is cylindrical in the cooling section by measuring it with scrapers [9]. However, the resolution of trajectory response measurements was found inadequate for tuning with the required accuracy, likely because of an insufficient number of the beam position monitors (BPMs) in combination with a drift of the electron trajectory. Scraper measurements showed that the beam had a large envelope modulation in the cooling section, which was predominantly axially symmetrical and was eliminated by

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adjusting the focusing strength of two solenoidal lenses right upstream of the cooling section (labelled SPB01 and SPB02 in Fig.1b). This tuning proved to be sufficient for demonstrating electron cooling and successfully applying it to cooling of antiprotons in the Recycler [1]. On the other hand, there were indications that the electron angles significantly increase toward the beam periphery. The angles of on-axis electrons were estimated from drag rate measurements [10] to be ~0.1 mrad [11]. This value was fed into BETACOOL [12] simulations of cooling rates for the case of comparable sizes of both beams. The simulated rates significantly exceeded the measured ones, and the discrepancy could only be mitigated 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, a YAG crystal [13] (Fig.1b), which had been installed into the Recycler vacuum chamber downstream of the 180-degree bend in 2004. When the bend is turned off, a cross section of a pulsed electron beam coming out of the cooling section can be observed on the crystal.

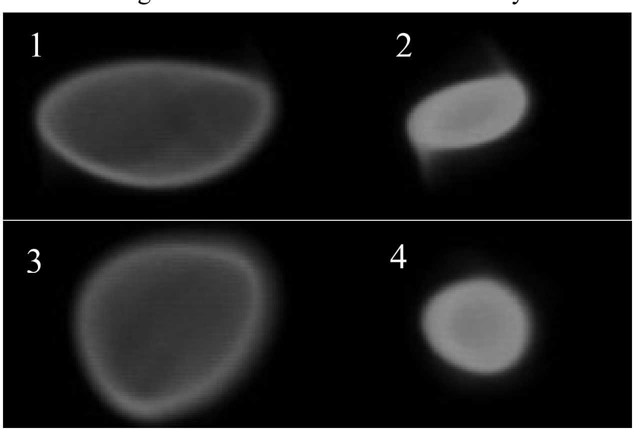

Figure 2: Images of the beam at the YAG with zero (1 and 2) and adjusted (3 and 4) quadrupole currents. Images were recorded at zero current of the lens SPQ01 (1 and 3) and at 10.4 A (2 and 4). All other settings are the same for all images. Beam current was 0.1 A, the pulse duration was 2 μs, and the camera was gated over a 100-ns window at the peak of the pulse.

The initial images showed a significant deviation from axially symmetrical shape (Fig.2). The main component, an elliptical distortion, was corrected by adjusting 6 quadrupoles upstream of the CS with a special procedure [14]. In successive steps, the current of each quadrupole was varied by a small amount and the resulting change of the ellipticity was recorded for two settings of the lens located between the CS and the YAG (labelled SPQQ01 in Fig. 1b). Then, a calculation with the 6 × 2 matrix of results gave the optimum values of the quadrupole currents to minimize the ellipticity. This process converged, and after several steps the beam cross section ellipticity was reduced to a few percent for any focusing of SPQ01 (Fig.2).

With the resulting quadrupole settings, the beam size was measured at the scintillator for various currents of SPQ01. From this data, the beam envelope in the CS was reconstructed and was found quite far from cylindrical. It was corrected by the proper adjustment of the lenses SPB01 and SPB02.

The manipulations described above were supposed to decrease the angles, and, correspondingly, dramatically increase the cooling force. However, the drag rate measurements that followed showed a slightly worse cooling force. We interpret this fact as an indication that accumulation of secondary ions in the beam line significantly affects the beam envelope in DC mode. Note that the plates of all BPMs in the cooler are used as ion cleaners, but there is no ion cleaning inside the solenoidal doublets.

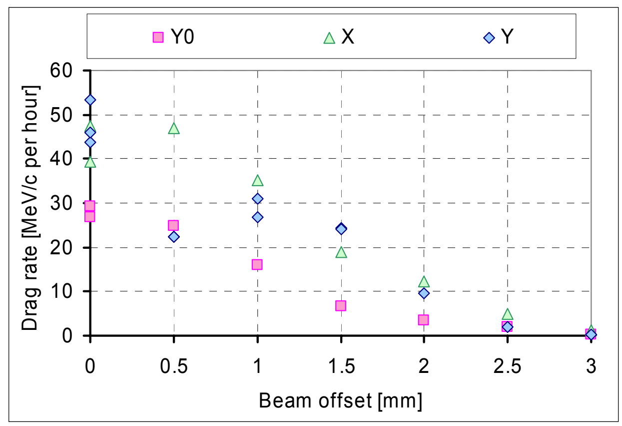

Figure 3: Drag rate as a function of the offsets between the antiproton and electron beams. The set labelled Y0 represents data recorded for vertical offsets before applying the quadrupole correction. The sets X and Y show the results after quadrupole correction for offsets in horizontal and vertical directions, correspondingly.

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 similar scans were made for the two lenses SPB01 and SPB02 in order to optimize the axially symmetrical perturbation. This procedure was repeated several times until no further increase of the drag rate was found. The resulting improvement at various relative offsets between the 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 the "pencil" antiproton beam, which is poorly controlled during the measurements. The cooling rate, the most relevant figure of merit for operation, increased considerably as well (Fig.4). At present, the cooler always operates with the electron beam at an offset of 0.5 – 2 mm that provides strong enough cooling while preventing an instability due to an overcooled beam.

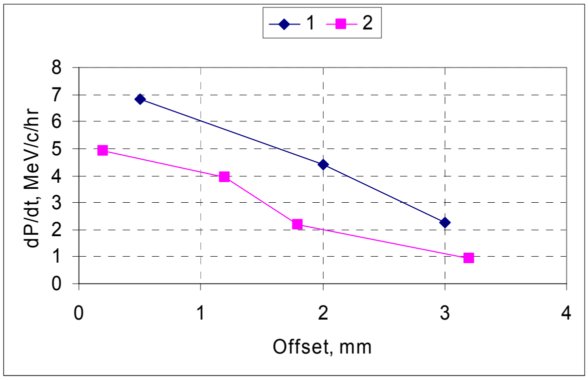

Figure 4: Comparison of the longitudinal cooling rates at various vertical offsets of the electron beam before (set 2) and after (set 1) adjustments of quadrupoles. Antiproton beam parameters for set 1/set 2: number of antiprotons 100/61 10^{10}, beam length 5.5/4.1 μs, transverse emittance measured with a flying wire 2.6/3.8 π 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 drag rates exceeding those measured at 0.1 A.

ELECTRON ENERGY STABILIZATION

The requirement of equality of electron and antiproton longitudinal velocities translates into a tolerance for electron energy deviations of 0.01%. With Recycler RF off, the position of the peak of the antiproton momentum Schottky distribution is the best indication of the electron energy, and it has been used for various calibration measurements. In routine operation, we rely first of all on the HV stability provided with the 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 the identification of 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. Now, the steady-state tank temperature is 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 the 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 SF_6 pressure at the rate of ~500 eV/psi because of the SF_6 permittivity. This is typically not an issue unless a gas leak develops.

In addition to efforts leading to temperature stabilization, the beam –based energy diagnostics is used in a dedicated software loop that adjusts 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 the Fermilab cooler's electron beam showed a significant quadrupole perturbation. This perturbation was decreased by adjusting quadrupoles upstream of the cooling section that significantly increased the cooling rate.
2. Improved temperature stabilization and implementation of a beam-based feedback energy regulation loop improved the long-term stability of the electron energy to 0.01%.

ACKNOWLEDGMENTS

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