# Attainment of a High-quality Electron Beam for Fermilab's 4.3 MeV cooler[1]

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**Abstract.** The recent demonstration of electron cooling of antiprotons in the Recycler ring required a stable 4.3 MeV electron beam with a DC current of hundreds of mA and an angular spread in the cooling section of a fraction of a mrad. This paper describes the achieved parameters of the Fermilab cooler's electron beam and details of operation.

**Keywords:** Electron cooling, electrostatic accelerator, electron beam
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## INTRODUCTION

In 2004-2005, an electron cooling device was installed in the Fermilab's Recycler ring to assist in accumulating and cooling a large number of antiprotons. While employing the same energy recovery (or recirculation) scheme as existing low-energy coolers, the Recycler electron cooler (REC) differs from them dramatically in several aspects. First, the REC electron energy of 4.32 MeV is higher by an order of magnitude; second, the gun cathode is immersed in a longitudinal magnetic field, but most of the beam transport line is field-free; third, the electrons are not heavily magnetized in the cooling section, making only two Larmor rotations over the section's 20 meter length; and finally, the cooler shares the tunnel with a 150-GeV synchrotron, the Main Injector (MI). These features make the machine commissioning and operation very specific. Below we describe the setup and the beam properties that allowed the first demonstration of electron cooling in the MeV electron energy range [1].

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# SETUP DESCRIPTION

The mechanical schematic of the setup is shown in Fig.1. The electron beam is generated by an electrostatic accelerator, the Pelletron [2], and transported through a beam “supply” line to the cooling section where it interacts with antiprotons circulating in the Recycler. After separation of the beams by a 180 degree bend, electrons move through the “return” beam line back to the Pelletron, are decelerated in the second Pelletron tube, and the beam is absorbed in a collector at the kinetic energy of 3.2 keV. The cooler optics is described in Ref. [3]. Some of the cooler parameters are listed in Table 1.

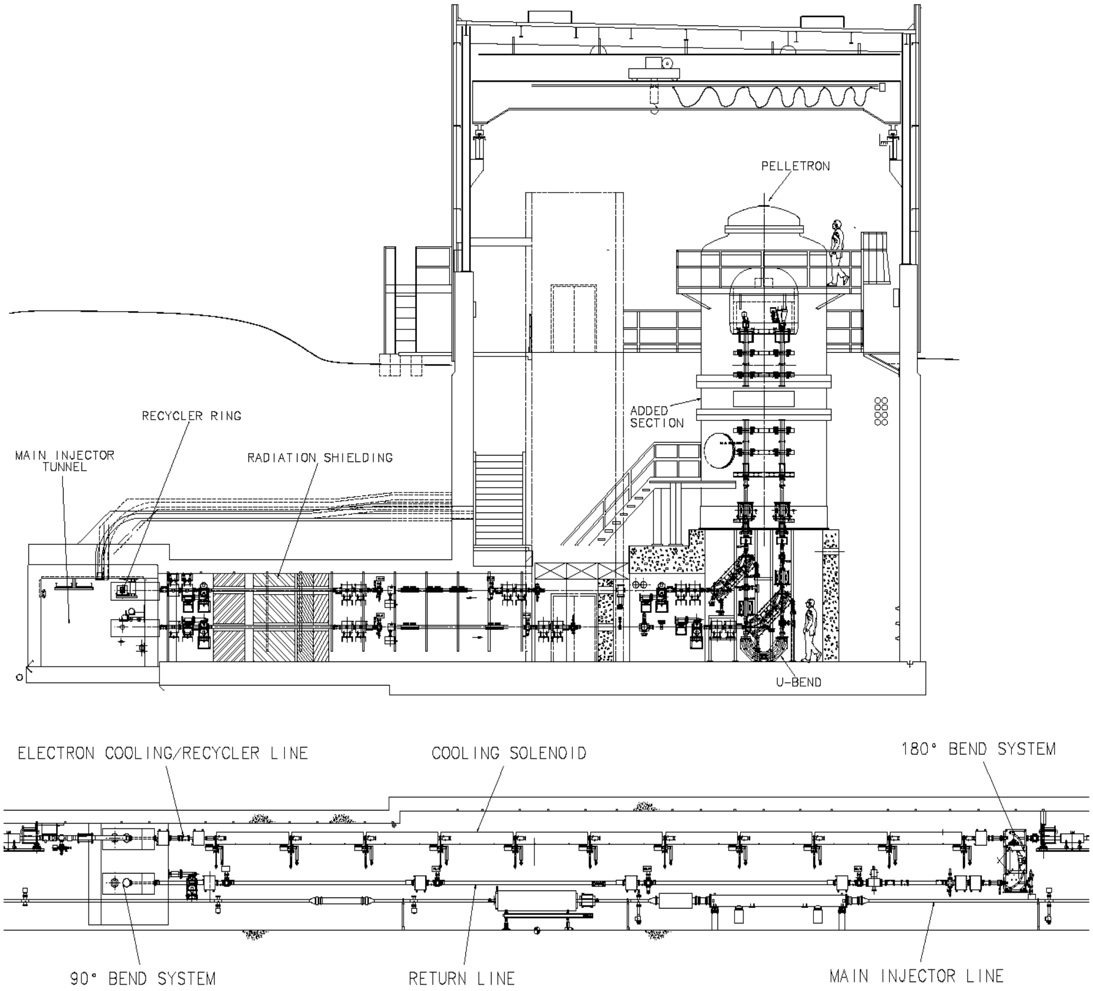

**FIGURE 1.** The top insert is an elevation view showing the Pelletron, the acceleration and deceleration beam lines, the transfer lines passing through connecting enclosure to Recycler ring, and the cross-section of the Main Injector tunnel which houses the Recycler ring. The bottom insert is an elevation 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.

The vacuum chamber is pumped down by ion and titanium sublimation pumps. The typical diameter of the beam line vacuum chamber is 75 mm, but the aperture is limited by the BPM’s inner diameter of 47 mm. In the cooling section, the beams see a

47 mm round chamber except for the narrow diagnostics/pumping gaps between modules.

When both main bending magnets under the Pelletron are turned off, the beam can be recirculated through a short beam line, denoted as U-bend in Fig.1. This so-called U- bend mode was used for commissioning purposes. For instance, in this mode we were able to reach DC beam currents up to 1 A at the nominal energy.

**TABLE 1 Some parameters of the cooler.**

| **Parameter** | **Unit** | **Value** |
|---|---|---|
| Electron energy | MeV | 4.338 |
| Beam current used for cooling | A | 0.2 |
| Maximum DC beam current | A | 0.6 |
| Magnetic field in the cooling section | G | 105 |
| Beam radius in the cooling section | mm | 4.2 |
| Pressure | nTorr | 0.2 - 1 |
| Total length of the beam line | m | 90 |

A simplified electrical schematic of the accelerator is shown in Fig.2. Typically, the Pelletron chain supplies 115 μA, from which 95 μA go to the resistive strings and 20 μA are used to provide the voltage stabilization and compensation of the beam loss.

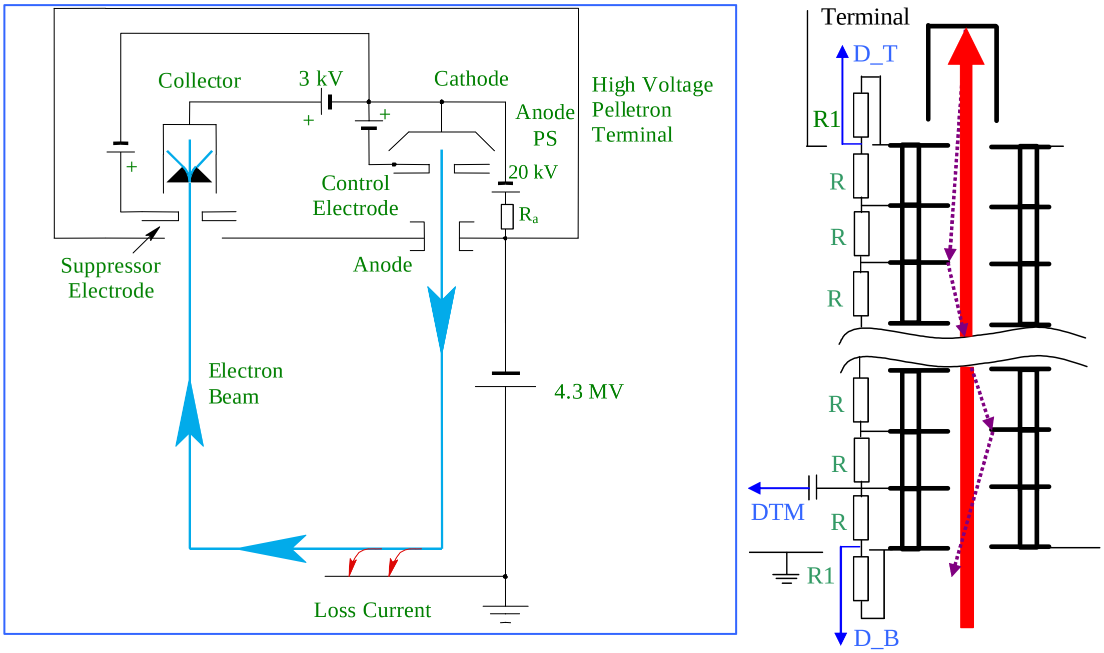

**Figure 2.** A simplified electrical schematic of the accelerator The left insert shows the recirculation scheme. The sketch on the right represents the deceleration tube with its resistive divider. The divider current is measured at the top (D_T) and at the bottom (D_B). Fast changes in the potential distribution along the tube can be analyzed by measuring the AC component of the signal from the last tube electrode (Tube Monitor, DTM). Diagnostics on the acceleration side are identical.

## Diagnostics

The beam line is equipped with several types of beam diagnostics. The beam trajectory is measured by 31 pairs of capacitive pickups, referred to further as BPMs

[4]. The BPMs can work in four modes: the pulse mode (2 μsec pulses at 1 Hz); negative pulsing, when a DC beam is interrupted for 2 μsec at 1 Hz rate; a sinusoidal modulation of a DC beam current at the frequency of 32 kHz; and the antiproton beam position measuring mode, when the signal is processed at the Recycler ring revolution frequency of 89 kHz.

Eleven scrapers, installed in the gaps between the modules of the cooling section, are used to measure the beam envelope. Each scraper is a retractable copper plate with a 15 mm round orifice. Also, in the pulse mode the beam size can be estimated by a multi-wire harp (fifty tungsten, 25-μm-diameter wires in each of two planes separated by 0.5 mm).

Several optical transition radiation (OTR) monitors have been installed in the beam line. However, unexpectedly high radiation from the Main Injector destroyed all cameras in the MI tunnel, and only two such monitors, located under the Pelletron, were used in measurements.

### Protection system

During operation of the cooler prototype, twice its vacuum chamber was drilled through by the electron beam. To avoid such accidents at the cooler, several layers of protection have been implemented.

The most important one is a system that closes the gun if the Pelletron terminal voltage drops due to large beam losses. A capacitive pickup plate, positioned at the Pelletron tank opposite to the terminal shell, measures the AC component of the terminal voltage, which is compared to a threshold. If the voltage drop is too large (usually > 5 kV), the gun is closed in ~ 1 μs.

In addition, a dedicated controller monitors radiation loss monitors placed around the cooler's beam line. Radiation above a preset threshold results in closing of the gun in ~ 1 ms. Finally, the control system prevents manipulating critical power supplies in an unsafe manner.

## RECIRCULATION STABILITY

To provide cooling, the electron beam should stay for hours at the nominal energy and the current of hundreds of mA. One of the necessary conditions for the stable operation is low current losses. At the beam current of 0.4 A, the relative value of the lost current is $1.2 \cdot 10^{-5}$ (Fig.3). Comparison of this number with the relative loss in the U-bend configuration, $6 \cdot 10^{-6}$, and with losses observed at a test bench, $\sim 2 \cdot 10^{-6}$ with the same collector, hints at a mechanism of losses dependent on the beam line length. The radiation monitors indicate that practically all losses occur under the deceleration tube; therefore, they are related to the collector efficiency. Simulations suggest that the mechanism is the reflection from the collector entrance of electrons that lost part of their energy due to intra-beam scattering [5].

At the level of 10 μA or below, this additional load for the Pelletron does not cause any problems for the voltage regulation. However, the part of losses coming to the tube electrodes redistributes the potential along the tube and may lead to full discharges. Ref. [6] describes our work to decrease the frequency of these discharges.

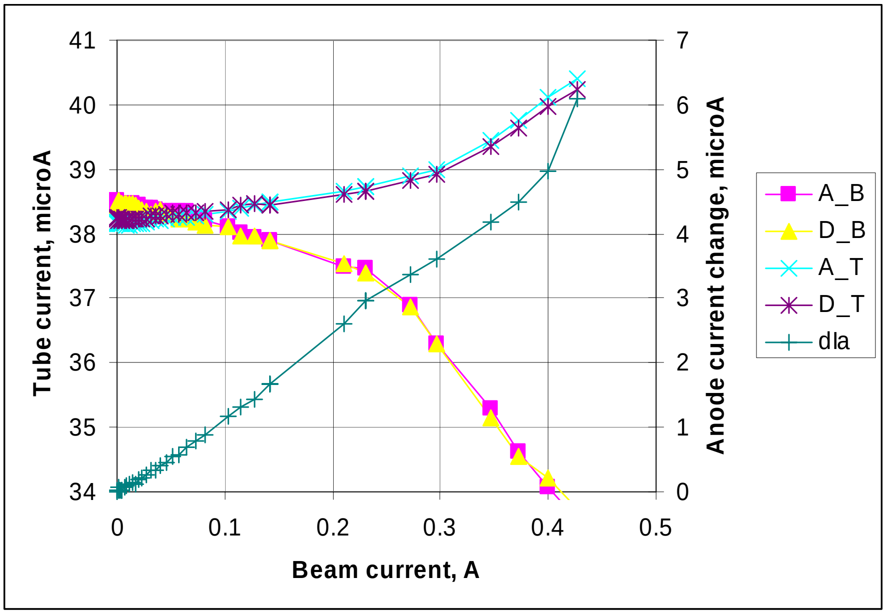

**Figure 3.** Current losses vs the beam current in the full beam line. dIa is the change in the anode current. The other four curves are currents of the resistive divider strings. ‘A’ and ‘D’ label the acceleration and deceleration tube strings, while ‘B’ and ‘T’ indicate readings at the bottom and top ends of the string (see Fig.2).

Significant difficulties in achieving a stable recirculation were caused by being in the neighborhood of the Main Injector (Fig. 4). When it ramps, stray magnetic fields from magnets and busses moved the electron beam, even though significant efforts had been made for proper shielding [7]. The beam motion in the return line was initially up to 6 mm and frequently resulted in the beam scraping either at a so-called crash scraper [6] or in the collector anode. Typically, losses were high enough to cause a recirculation interruption. The main reason for the extensive motion was found in an inadequate compensation of the MI buss currents. Magnetic shielding around the busses does not suppress the magnetic field generated by a non-zero total current summed over all busses and a dedicated compensation wire, running near the busses around the entire 3.3 km ring. A proper adjustment of the current in the wire as well as a modification of the return line shielding decreased the electron beam motion amplitude to 2 mm in the worst location. In addition, shortening of the protection system’s response time from 0.8 ms to ~1 μs allowed operation with the crash scraper removed [5], which dramatically freed the beam line aperture. Presently, the beam motion in the return line does not significantly affect the recirculation stability.

Another difficulty is the losses of the MI proton beam that sometimes produce the radiation high enough to trip the electron beam protection system. Eventually we set the trip level above possible MI- initiated jumps of radiation. This value corresponds to an electron beam loss of about 20 μA, which is considered to be an upper boundary from the point of view of damaging the vacuum chamber.

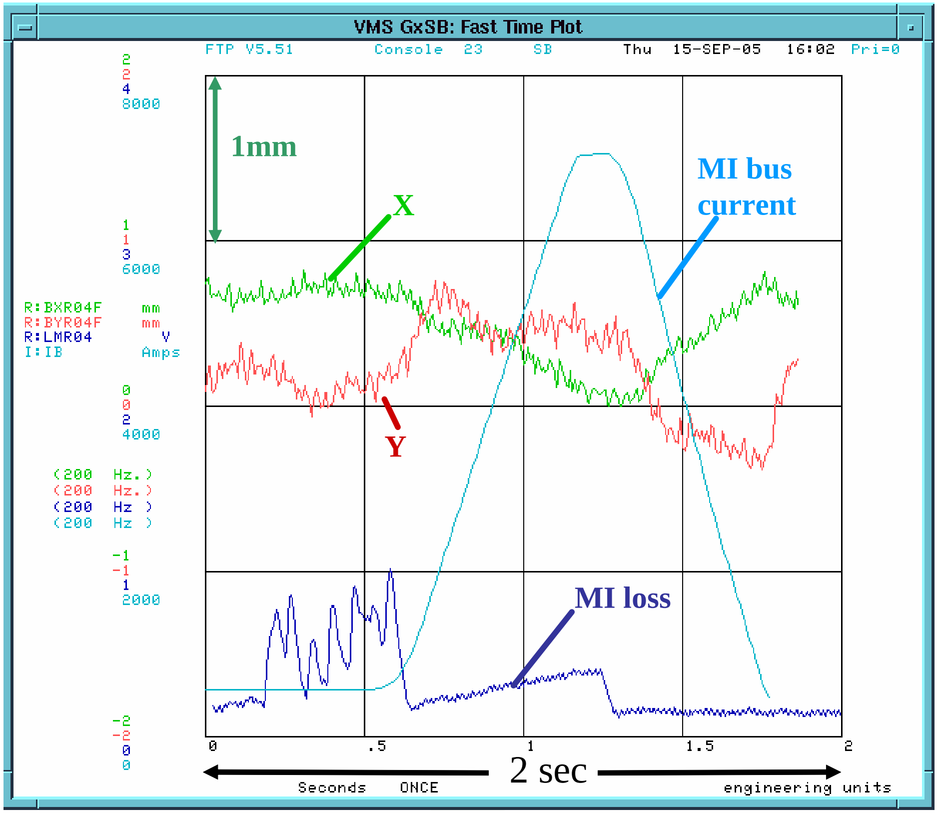

**Figure 4.** MI bus current, electron beam positions (X and Y), and radiation monitor signal in the return line in a typical MI ramp. A case of a low MI loss is shown. The 0.55 Hz oscillations outside the ramp are due to a 250 V r.m.s. ripple of the Pelletron voltage, because the dispersion in this location is 3 m.

At the nominal beam currents of 0.2 A, recirculation interruptions are observed once in several hours, and full discharges occur once in several weeks until the deceleration tube looses its electric strength. Several parameters in a 24 hours span including a full discharge are shown in Fig. 5.

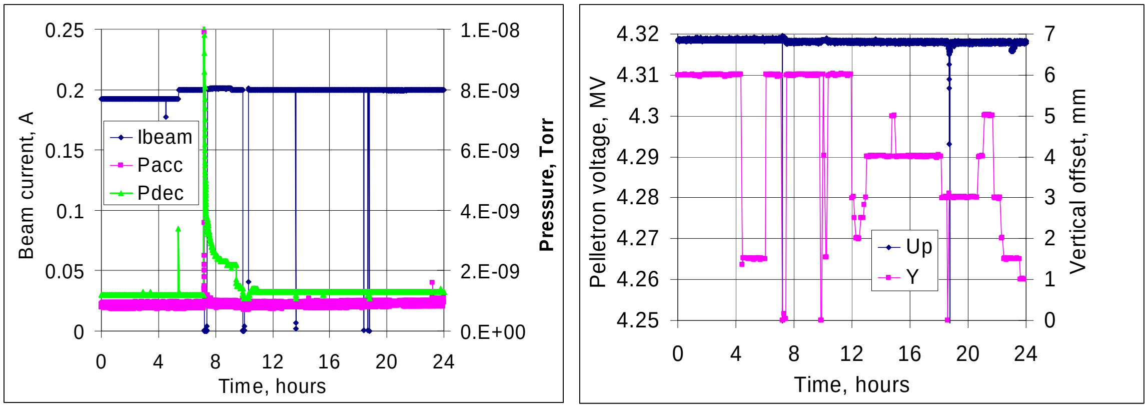

**Figure 5.** 24 hours of running the electron beam. Curves are labeled as follows: Ibeam is the electron beam current, Pacc is the pressure measured by an ion pump under the acceleration tube, Pdec is the pressure measured by an ion gauge under the deceleration tube, Up is the Pelletron voltage, and Y is the vertical offset in the cooling section. A large perturbation of Pdec corresponds to a full discharge. The vertical offset adjustments reflect regulation of the cooling strength.

## ELECTRON BEAM PROPERTIES

For an effective cooling, the electron energy spread and the electron angles should be lower than the corresponding antiproton values. Also, the beams have to be well aligned in space and in momentum.

### Electron Energy

Preliminary calibration of the electron energy was made by measuring of the length of a Larmor spiral pitch in the cooling section [8]. The precision, determined by the calibration of the Hall probe used for the longitudinal field measurements and by errors of the beam position measurements, was estimated to be ±0.2%. Comparison of the nominal Recycler energy with the energy of a low intensity, electron-cooled coasting antiproton beam shown that the actual discrepancy between both beams' energy calibration was $5{\cdot}10^{-4}$ [1]. While continuously running, the relative drift of the electron energy is about $3{\cdot}10^{-5}$; shutting the Pelletron off for a shift may result in changes of $1{\cdot}10^{-4}$; and opening the Pelletron and removing the terminal shell might modify the calibration by up to $3{\cdot}10^{-4}$.

The effective energy spread is determined by the electron energy distribution and fluctuations of the Pelletron voltage. The first component is calculated in Ref. [5] to be ~100 eV. The voltage fluctuations can be estimated by the signal from capacitive pickups in the tank and by beam motion in a high-dispersion region (Fig. 4). Both methods give the r.m.s. value of 250 V. Therefore, the effective energy spread is about 270 eV.

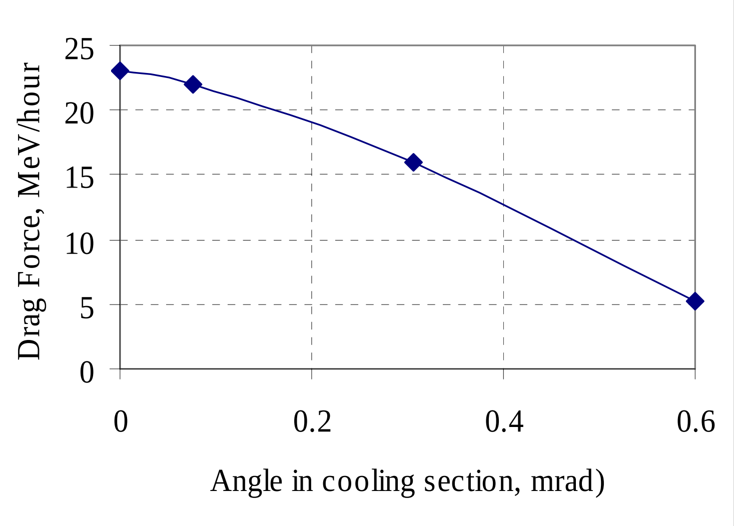

**Figure 6.** Drag force as a function of the dipole angle in the cooling section. The angle is applied with a corrector at the entrance of the cooling section and measured by BPMs. The drag force is measured by tracing the change of the average pbar energy after a 1 kV shift of the Pelletron voltage. The data were acquired with coasting $4{\cdot}10^{10}$ pbars, transverse emittance of 1.4 $\pi$ mm mrad (95%, normalized), and the initial pbar momentum spread of 0.8 MeV/c (90%).

### Electron Angles

Analysis of the electron angles in the cooling section, presented in Ref. [3], shows that presently the angles across the beam are determined by envelope oscillations. The original design assumed operation of the gun in the Pierce mode, with a nearly uniform current density distribution. However, stable operation at 0.7 A, which corresponds to this regime, has not been achieved, and the gun runs at 0.2 A with both current and angle distributions far from being homogeneous. The only diagnostics available for envelope angle measurements in the cooling section is a set of scrapers [9], and it allows aligning trajectories of outside electrons. While the gun aberrations do not contribute significantly into the angle spread in the beam core, the angles of the boundary particles may be far from a simple linear dependence on the radial offset. As a result, the procedure has provided angles low enough to make electron cooling operational, but still much higher than the 0.1 mrad initially foreseen for this angle component.

The large envelope oscillations of the beam core can be the reason for the observed sharp dependence of the drag force on the beam offset. The measurements were made with a low intensity, cold antiproton beam (see details in Ref. [1]) and shown that the drag force drops from ~ 20 MeV/h in the center to ~10 MeV/h with the 1 mm offset to ~5 MeV/h with 2 mm offset. Another indication of large envelope angles is a smooth dependence of the drag force on the amplitude of a dipole kick given to the beam at the entrance of the cooling section (Fig. 6). We estimate that while the electron angles near the axis are ~ 0.1 mrad, the maximum angles in the beam can be as high as 0.4 mrad.

## OPERATIONAL ASPECTS

Electron cooling is now routinely used for storing and cooling of antiprotons in the Recycler ring. It was observed that overcooling may result in beam instability, a growth of the transverse emittance, and shortening of the beam life time. Two methods are used to regulate the cooling strength: changing the beam current or the electron beam offset.

Increasing the beam current from zero to 0.2 A decreases monotonically the equilibrium antiproton longitudinal emittance. Note that a further rise of the current does not lower this equilibrium. It may be explained by changes in the beam envelope, because for optimum cooling the focusing settings should be adjusted for every beam current.

More often, the cooling strength is regulated by a parallel shift of the electron beam in the cooling section. Because of the high energy, the electron beam space charge does not affect the pbar dynamics. Also, the combination of a long cooling time and large coupling in the Recycler ring allows cooling of all degrees of freedom even if the electron beam stays at a fix position off axis. As a result, cooling with at a constant 0.2 A current and the offset varying between 1 and 5 mm is at least as good operationally as on-axis cooling at lower currents. Although the life time deterioration has not been studied to the level of making a reliable conclusion about benefits of this mode, one can speculate that off-axis cooling may alleviate instabilities related to an overcooled antiproton beam core. In addition to cooling off axis, we plan to try cooling slightly off energy. Combined with containment of the beam in a barrier bucket, off energy cooling might be beneficial due to a flattened equilibrium momentum distribution.

## SUMMARY

Electron cooling of 8 GeV antiprotons has been demonstrated and is presently in a routine operation.

- Recirculation is stable enough for the electron beam currents up to 0.2 A but drops for currents above 0.3 A because of increasing probability of full discharges.
- Electron angles in the cooling section are determined by envelope scalloping.
- In operation, the cooling strength is regulated by parallel shifts of the electron beam with respect to the antiproton beam.

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