

## Status of High Energy Electron Cooling in FNAL's Recycler Ring\*

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### Abstract

Electron cooling of 8 GeV antiprotons at Fermilab's Recycler storage ring is now routinely used in the collider operation. It requires a 0.1-0.5 A, 4.3 MeV DC electron beam to increase the longitudinal phase-space density of the circulating antiproton beam. This paper discusses the latest status of the electron cooler and its mode of operation within the context of Fermilab's accelerator complex. In addition, we will show preliminary results that demonstrate electron cooling of the transverse phase-space of the antiproton beam.

## INTRODUCTION

Since the end of the commissioning period, marked by the first demonstration of electron cooling of 8 GeV antiprotons in the Recycler storage ring in July 2005 [1], the electron cooler [2] has been used for storing and preparing antiproton bunches for nearly every Tevatron store. At the same time, significant efforts were put into improving the stability of operation and the electron beam quality as well as measuring and understanding the cooling properties of the electron beam.

## ELECTRON BEAM STABILITY AND CHARACTERISTICS

### Stability of the beam generation

The cooler employs a DC electron beam generated in an electrostatic accelerator, Pelletron [3], operated in the energy-recovery mode. Detailed descriptions of the beam line configuration can be found in Refs [1,2,4]. The main parameters of the cooler are summarized in Table 1.

Table 1: Electron cooler main parameters

Parameter	Symbol	Value	Unit
Electron kinetic energy	$E_b$	4.34	MeV
Beam current	$I_b$	0.1-0.5	A
High voltage ripple, rms	$\delta U$	250	V
CS length	$L$	20	m
Solenoid field in CS	$B_{cs}$	105	G
Beam radius in CS	$R_p$	3-4.5	mm

Operation and integrity of the cooler can be compromised by full discharges, where the Pelletron voltage drops to zero in a sub- $\mu$ s time, and the pressure in one of the acceleration tubes increases by several orders of magnitude. Thanks to preliminary simulations [5], various modifications to the protection system [5] and extensive tuning of the beam (focusing and steering) in the deceleration tube [6], stable operation was achieved at  $I_b = 0.5$  A. The average frequency of full discharges was once per two days but increased significantly after two

months of operation at this intensity. Because cooling at high current is not found to be beneficial (see below), the operational current was decreased to 0.1 A. At this value, after Fermilab's 2006 annual long shutdown, only one full discharge was recorded over a period of three months for a duty factor of 50% (i.e.  $\sim 12$  hours of continuous running time a day). The reason for the stability degradation at 0.5 A is still not understood.

### Electron beam quality

The main figures of merit to assess the quality of the electron beam and its ultimate cooling capability are the energy spread,  $\sigma_E$ , the beam current density,  $J_{cs}$ , and the rms value of the electron angles in the cooling section (CS),  $\alpha$ .

The effective electron energy spread is dominated by the Pelletron HV ripple,  $\delta U = 250$  V rms. Multiple-coulomb scattering and electron beam density fluctuations [7] are estimated to contribute  $\sim 100$  eV, added in quadrature.

The current density in the cooling section,  $J_{cs}$ , can be estimated from the simulated current density at the cathode,  $J_{cath}$ , and either direct measurements of the beam radius in the cooling section with movable orifices [8] or based on equality of magnetic fluxes in the CS and at the cathode. For  $I_b = 0.1$  A,  $J_{cs}$  on axis is calculated to be  $0.6$  A  $\text{cm}^{-2}$  from beam radius measurements and  $1.0$  A  $\text{cm}^{-2}$  from magnetic measurements. To explain this discrepancy, it was proposed that secondary electrons might be trapped in the cooling section, thus reducing focusing of the primary beam and leading to a larger beam radius [6] than expected from magnetic measurements. A more direct proof of the presence of secondary electrons is yet to be found.

The rms value of the electron angles in the CS has several origins including beam envelope scalloping, dipole magnetic field imperfections and drift velocity. Diagnostics such as an optical transition radiation detector (OTR), beam position monitors (BPM) and movable orifices were used to estimate each component independently. From these measurements (and calculation for the drift velocity), our current estimate for the total angles (averaged over time, beam cross section and CS length) is 0.2 mrad. Note that the drift velocity calculation does not take into account the possible presence of secondary electrons and could be significantly different.

## LONGITUDINAL COOLING FORCE MEASUREMENTS

The cooling properties of the electron beam are evaluated with drag rate measurements by a voltage jump method [9] and with diffusion measurements [10]. From these, the cooling force as a function of the antiproton

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momentum deviation from the Recycler nominal momentum is obtained. Then, the results are fitted to a non-magnetized model [11], for which  $J_{CS}$ ,  $\alpha$ , and  $\sigma_E$  are free parameters. The fitted values for the drag rate measurements with the voltage jump method differ from those discussed in the previous section by a factor of 1.5 - 2 (Table 2).

Table 2: Comparison of the electron beam main parameters obtained from fit to the drag rate data and estimates based on other independent measurements. This is for the case of a 100 mA electron beam.  $J_{CS}$  is estimated on-axis. The Coulomb log is 10 for the fits.

	Fit	Estimates
$J_{CS}$ , A cm <sup>-2</sup>	1.2	0.6-1.0
$\theta_e$ , mrad	0.19	0.2
$\delta E$ , eV	370	250

While a statistical error of an individual drag measurement is 2 - 7%, variation in data measured in different days and months was much larger, up to a factor of 2. So far no satisfactory explanation has been found. The maximum recorded drag rate is 37 MeV/c per hour for  $I_b = 0.2$  A. However, going to higher currents did not lead to higher drag rates.

More details regarding the drag rate measurements can be found in Refs. [6,12] and in Ref. [10] for the diffusion method.

## TRANSVERSE COOLING

Following the 2006 annual shutdown period, we have observed significant transverse cooling rates when the electron beam is on axis. Figure 1 shows the evolution of the transverse emittances (95%, normalized, taken as  $6\times$  the rms emittance) for the case where a 100 mA electron beam was brought on axis and stochastic cooling is turned off. Two independent detectors are used for these measurements: a Schottky monitor and flying wires. The increasing divergence between the two emittance measurements is explained by the fact that under electron cooling, the transverse distribution deviates from Gaussian, as illustrated in Figure 2. On one hand, the flying wire data analysis software fits the data to a Gaussian distribution from which it extracts its second moment. On the other hand, the Schottky detector computes the true rms of the distribution it captures. In some sense, the flying wire data give the emittance evolution of the core of the antiproton bunch, while the Shottky monitor is significantly affected by the tails of the distribution. The presence of these tails is also responsible for some of the discrepancy between the absolute values reported by the two detectors. The signal-to-noise ratio (S/N) of the Schottky detector is one to two orders of magnitude larger than the S/N ratio of the flying wires, thus more sensitive to the tail population.

So far, the minimum observed transverse e-folding cooling time was 25 min (flying wire), which is close to values obtained for the stochastic cooling system for the

same intensity ( $\sim 150\times 10^{10}$ ). Note that a typical transverse growth rate in the Recycler is  $\sim 1 \pi$  mm mrad per hour when no cooling is applied.

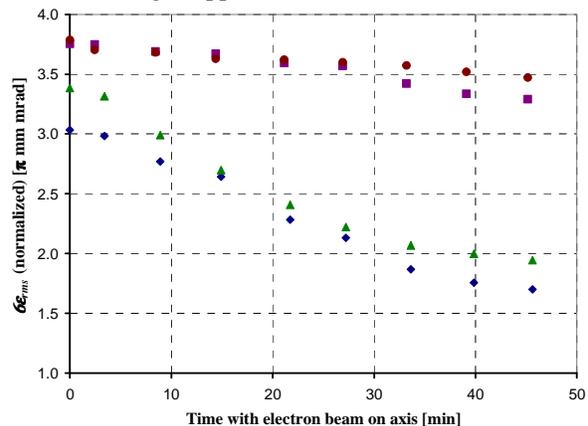


Figure 1: Emittances evolution with the electron beam on axis, 100 mA and stochastic cooling off. Blue diamonds and green triangles are the horizontal and vertical emittances from flying wire measurements. Brown circle and purple squares are the same emittances but measured with a 1.75 GHz Schottky detector.  $N_p = 188\times 10^{10}$  antiprotons, bunch length = 6.1  $\mu$ s.

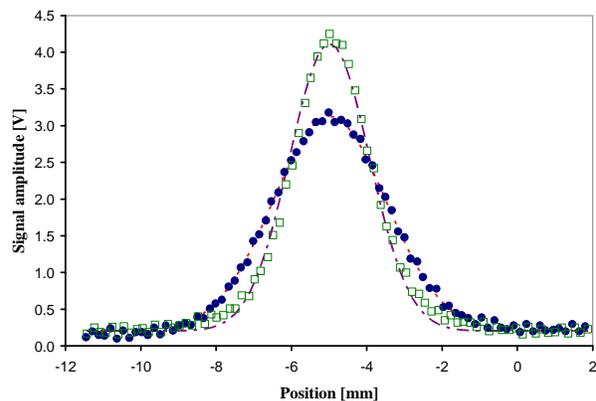


Figure 2: Horizontal antiproton beam profiles before (blue circles) and after (green squares) 60 minutes with the electron beam at 100 mA and on axis. The dotted lines are the best Gaussian fits to the data (with no background subtraction).  $N_p = 135\times 10^{10}$  antiprotons, bunch length = 6.5  $\mu$ s (kept constant)

## ELECTRON COOLING IN OPERATION

Electron cooling is routinely used in operation, and stacks of up to  $4\times 10^{12}$  antiprotons were cooled to the target longitudinal emittance for shots to the Tevatron.

Comparison of longitudinal cooling rates at various currents shows a trend similar to the one found with drag rate measurements, namely that the cooling rate is practically constant above 0.1-0.2 A. Consequently, all cooling is carried out at 0.1 A with adjustments of the cooling rate done by vertically shifting the electron beam in and out of the antiproton beam.

Figure 3 shows the longitudinal emittance evolution when the electron beam is brought on axis (100 mA) and provides maximum cooling. In this case, the e-folding cooling time is 20 minutes. Note that because the lifetime deteriorates under these conditions, this is not typically the way the cooling procedure is implemented and maximum cooling is only provided when extraction is imminent. Consequently, the operational cooling time is close to 1h. A more detailed discussion of the operational aspects related to electron cooling can be found in Ref. [12].

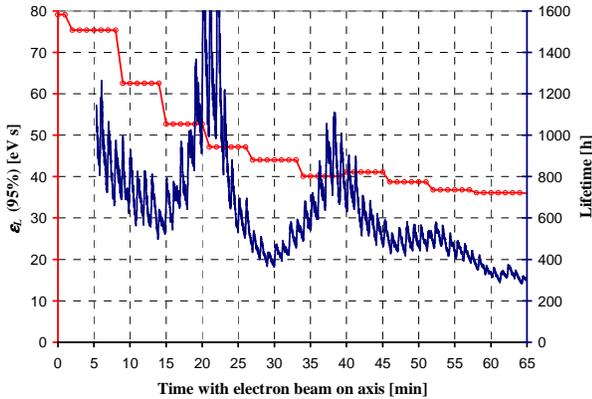


Figure 3: Longitudinal emittance (red circles) and antiproton lifetime (blue) – 10 minutes running average - with a 100 mA electron beam on axis (stochastic cooling off).  $N_p = 111 \times 10^{10}$  antiprotons, bunch length =  $5.2 \mu\text{s}$  (kept constant); tunes are 25.456/24.462 (H/V).

For reasons not yet understood, the very poor lifetime reported in Ref. [12] under strong electron cooling has been less severe since the end of the 2006 annual shutdown. Although the antiproton beam remains affected by the presence of the electron beam, even if it is not matched to the antiproton momentum, the lifetime degrades much slower (more than  $2\times$ ) than pre-shutdown running at the same operating point. In fact, we have been able to ‘mine’ [13] the antiproton bunch while maintaining good lifetime - in the range of 500 hours - for stacks of up to  $300 \times 10^{10}$  antiprotons, which are stored in the Recycler for 20-30 hours.

In addition, although it has already been established that the presence of the electron beam plays an important role in the transverse emittance growth that we experience at the mining stage [12], it is now clear that the quadrupole instability theory which was proposed to explain it [14] is not the only mechanism. It is for instance striking that even when the electron beam is turned off minutes before the mining sequence starts, non-negligible growth of the transverse emittance is recorded when running at our ‘lower’ operating point (25.414/24.422, H/V tunes) but not at our current operating point (25.452/24.469). More investigations are under way.

Although stochastic cooling and electron cooling have been employed together successfully, progressing towards larger and denser stacks of antiprotons brings new issues. In particular, when the antiproton beam is

being cooled aggressively with the electron beam, the peak current density increases rapidly. Then, if not properly adjusted for, the stochastic cooling system could heat the beam considerably, causing large emittance growth or beam loss.

Since the implementation of electron cooling, the number and phase-space density of the antiprotons available for luminosity production has significantly increased. Consequently, it directly contributed to Fermilab’s latest luminosity records.

## CONCLUSION

Fermilab has a unique electron cooling system routinely used for cooling 8.9 GeV/c antiprotons in the Recycler ring. Although only 0.1 A is needed to achieve the target longitudinal emittance (50-60 eV s) in the appropriate amount of time, reliable operation and cooling at DC beam currents up to 0.5 A has been demonstrated.

The longitudinal cooling force has been measured and agrees to within a factor of 2 with a non-magnetized model. Transverse cooling due to the electron beam has been recently observed and will be studied further.

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## REFERENCES

- [1] S. Nagaitsev *et al.*, Phys. Rev. Lett. **96**, 044801 (2006)
- [2] A. Shemyakin *et al.*, AIP Conf. Proc. **821** (2006) 280
- [3] Pelletrons are manufactured by the National Electrostatics Corporation, [www.pelletron.com](http://www.pelletron.com).
- [4] S. Nagaitsev *et al.*, AIP Conf. Proc. **821** (2006), 39
- [5] L.Prost and A.Shemyakin, AIP Conf. Proc. **821** (2006) 391
- [6] A. Shemyakin *et al.*, to be published in Proc. of EPAC’06, Edinburgh, UK, June 26-30, 2006
- [7] A.Burov *et al.*, AIP Conf. Proc. **821** (2006) 159
- [8] T.K.Kroc *et al.*, AIP Conf. Proc. **821** (2006) 370
- [9] H. Danared *et al.*, Phys. Rev. Lett. **72** (1994) 3775
- [10] D. Broemmelsiek and S. Nagaitsev, to be published in Proc. of EPAC’06, Edinburgh, UK, June 26-30, 2006
- [11] Ya.S. Derbenev and A.N. Skrinsky, Particle Accelerators **8** (1977) 1
- [12] L.Prost *et al.*, to be published in Proc. of HB2006, Tsukuba, Japan, May 29-June 2, 2006
- [13] ‘Mining’ is the first step in the extraction process that consists of capturing the core of the antiproton beam in 9 individual square buckets, leaving out the high momentum particles
- [14] A. Burov, to be published in Proc. of HB2006, Tsukuba, Japan, May 29-June 2, 2006