Electron Cooling in the Recycler Ring

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Tevatron luminosity and antiprotons

The Tevatron luminosity is linear with the total number of antiprotons available for the Tevatron store.

The antiproton beam quality is characterized by the phase-space density. To achieve higher luminosity this density needs to be increased.
Electron cooling in the Recycler Ring eliminates one of the bottlenecks in the long chain of the antiproton production.

Fermilab’s antiproton production chain

Proton beam

Inconel target

8 GeV

Debuncher (stochastic cooling)

Accumulator (stochastic cooling)

1 TeV

Tevatron

150 GeV

Main injector

Recycler (stochastic and electron cooling)

Electron Cooling - Shemyakin
The idea of electron cooling is a heat exchange through Coulomb scattering between hot heavy particles (antiprotons) and cold electrons while the beams are mixed in a cooling section.

- Was invented in 1967 by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.
- First tested in 1974 with 68 MeV protons at NAP-M storage ring at INP (Novosibirsk).
- CERN- ICE 1977 – 1979
- Fermilab 1979 - 1982
Low energy coolers

- Well – established techniques for electron energies below 300 keV.
  - A strong, continuous longitudinal magnetic field from the gun to the collector
  - An electrostatic accelerator working in the energy-recovery mode

Example of a 300 keV, 3 A cooler produced by Budker INP for IMP, Lanzhou (China).

The voltage difference between the gun and collector ~ 3 kV.
Difficulties of implementing at relativistic energies

- High electron beam power:
  - $4 \text{ MeV} \times 0.5 \text{ A} = 2 \text{ MW DC!}$

- Beam quality:
  - The electron beam temperature (in the rest frame) should be comparable with the cathode temperature of 1200K (only a factor of $\sim 10$ increase is allowed for the transverse degree of freedom)

<table>
<thead>
<tr>
<th>Design parameters of the RR ECool beam</th>
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<tr>
<td>Energy</td>
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<td>Beam current</td>
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<td>Angular spread</td>
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<td>Effective energy spread</td>
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History of relativistic electron cooling

- Fermilab, 1983: D. Cline et al., “Intermediate energy electron cooling for antiproton sources using a Pelletron accelerator”
  - For a pulsed electron beam in a Pelletron the beam quality is adequate for electron cooling

- Novosibirsk, 1987: successfully tested a prototype 1-MV, 1-A electron beam system.
  - Continuous magnetic field
  - Acceleration tubes are not sensitive to vacuum UV

- Fermilab, UCLA, NEC, 1989: tested a 2-MV, 0.1-A DC recirculation system with a Pelletron.
  - Poor stability

- Fermilab, IUCF, NEC, 1995: started to work on a 2-MV Pelletron again- beginning of the RR ECool project


**Premise**

- Solution for a high-power beam generator: use of a “standard” electrostatic accelerator (**Pelletron**) and non-standard focusing scheme
  - Recirculation (energy/charge recovery) scheme
  - No continuous magnetic field
  - A low-magnitude longitudinal magnetic field in the cooling section and at the cathode, but a lumped focusing in the remaining part of the beam line

- Failure of the previous attempt was recognized to be caused by high losses in the acceleration tubes
  - Current losses needs to be decreased below 0.01%

- New solutions for the gun and collector were found.
  - A gun with a negatively biased control electrode to suppress the beam halo and provide the beam transport at all currents
  - Effective suppressing of secondary electrons in the collector can be done by applying a transverse field in the collector cavity
**GOAL**

To demonstrate a stable (~1 hour) generation of a 0.2 A relativistic beam using an existing 2 MV Pelletron at NEC

Nov. 95: project started  
Jan. 97: first recirculated current (10 µA)  
Dec. 97: Max. recirculated current of 0.2 A  
May. 98: 0.2 A for 1 hours at 1.3 MeV  
Dec. 98: Max. current of 0.7 A  
Jan. 99: Gun solenoid (200 G) installed  
Feb. 99: 5 MeV Pelletron ordered  
May. 99: 0.9 A with 200 G at the cathode

How to scale the result for 1.3 MeV beam in a 2-MV tubes to a 4.3 MeV beam in a 5-MV accelerator?
**GOAL:** To demonstrate a stable generation of a 0.5 A, 4.34 MeV beam in a short beam line

Feb 99: 5 MV Pelletron ordered.

May 01: First beam of 30 μA in the collector.

Dec 01: 0.5 A at 3.5 MV

Apr 02: NEC replaced acceleration tubes

Oct 02: 0.5 A at 4.34 MeV

Nov 02: \( I_{\text{max}} = 1.7 \text{ A at 3.5 MV} \)

Shut down to install the full beamline

- New means to improve **stability**: ion stoppers, crash scraper, closing the gun in 1 ms
- **Diagnostics:** BPMs, scrapers, flying wire
- Operation was stable only at 3.5 MV. The tubes clearly needed to be **extended**.
- Now the main question was the beam **quality**.
Stage III – full-length line at WideBand

- The beam line was very similar to the final one at MI-31
- A novel type of the beam optics, angular momentum–dominated
- Developed a technique of precise measurements of the solenoid field quality
- Beam envelope measurements with movable orifices
- Final version of BPM electronics

- Jul-03 - first DC beam in the full-scale line
- Dec-03 - 0.5 A DC beam
- May-04 - 0.1 A beam with required properties in the cooling section
Final stage- Cooler in the Recycler

- Oct 2004- magnetic measurements in cooling section
- Apr 2005- first DC beam in the collector passed through the cooling section
Difficulties (some of them) and solutions

- Full discharges
  - Improvements in the protection system (closing the gun in 1 μs)
  - Minimizing current losses to acceleration tubes (dI/I <10^-5)

- Magnetic fields from the Main Injector
  - Compensation of bus currents, additional shielding
  - Changes in optics that made the system more tolerable to the beam motion

- Field angles
  - Magnetic field measurements were supplemented by a special tuning procedure employed Beam Position Monitors (BMPs)

- Energy matching
  - Absolute energy calibration of the electron beam by measuring the wave length of the electron rotation in the magnetic field of the cooling section
  - A special wide energy distribution of antiprotons to observe the first interaction between beams
Cooling

- First interaction - July 9, 2005
- First cooling - July 11, 2005
- First electron cooling-assisted shot to Tevatron - July 12, 2005

One of the first indications of interaction between antiprotons and electrons.
The plot shows evolution of antiproton energy distribution (log scale) after turning on an electron beam. Initially antiprotons occupy the entire momentum aperture of the Recycler.
Drag Force as a function of the antiproton momentum deviation 
100 mA, nominal cooling settings
Experimental Demonstration of Relativistic Electron Cooling

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We report on an experimental demonstration of electron cooling of high-energy antiprotons circulating in a storage ring. In our experiments, electron cooling, a well-established method at low energies (<500 MeV/nucleon), was carried out in a new region of beam parameters, requiring a multi-MeV dc electron beam and an unusual beam transport line. In this Letter, we present the results of the longitudinal cooling force measurements and compare them with theoretical predictions.

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Lack of radiation damping for heavy particles complicates their accumulation. The total six-dimensional phase-space density of antiproton beams, produced by striking dense targets with high-energy protons, cannot be increased by external fields independent of the particle motion [1]. In 1967, Budker described the method of “electron cooling,” a method of damping through the interaction between the antiproton (or proton) and an electron beam propagating together at the same average ve-
Electron cooling between transfers/extraction

- **Electron beam current**: 0.1 A/div
- **Transverse emittance**: 1.5 π mm mrad/div
- **Electron beam position**: 2 mm/div
- **Longitudinal emittance** (circle): 25 eVs/div
- **Pbar intensity** (circle): 16e10/div

**Stochastic cooling after injection**

- **Electron beam ‘out’** (5 mm offset)
- **Electron beam is moved ‘in’**

- **Pbar intensity**: 254e10
- **Electron beam current**: 195e10
- **Electron beam position**: 2 mm/div
- **Longitudinal emittance (circle)**: 25 eVs/div
- **Pbar intensity (circle)**: 16e10/div

~60 eVs

~1 hour
Evolution of the number of antiprotons available from the Recycler

01/10/05 – 02/18/06

Number of antiprotons ($x 10^{10}$)

Mixed mode operation

Ecool implementation

Recycler only shots
Remaining questions

- **Life time**
  - The antiproton lifetime suffers at strong electron cooling
  - Effect is not dramatic, but its removal will add additional percents to the number of antiprotons in Tevatron

- **Ultimate strength of cooling**
  - ECool works at $300 \cdot 10^{10}$, but additional work may be needed to cool effectively $600 \cdot 10^{10}$.
Summary

- The relativistic, non-magnetized electron cooling has been demonstrated
  - Allows other laboratories to proceed with further developments:
    - BNL - electron cooling at RHIC, $E_e = 54$ MeV
    - GSI & TSL - fast cooling of antiprotons, $E_e = 4 - 8$ MeV

- Fermilab has a world-record electron cooling system that has allowed recent advances in luminosity

- A hard limit on the maximum number of antiprotons in the Recycler has been removed. The road to higher luminosities is open.
The team (at the final stages)

- **Beam studies**
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