ELECTRON COOLING FOR THE FERMILAB RECYCLER RING

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Abstract

Although electron cooling[1] has been a routine tool in many laboratories, its use has been restricted to low energy accelerators (< 500 MeV/nucleon). Fermilab has undertaken a development program[2] in high energy electron cooling focused on accumulating 8 GeV antiprotons in a new storage ring, Recycler[3], that follows the Accumulator ring and is installed in the Main Injector tunnel. The ultimate goal is to realize a luminosity of 10^{33} $cm^{-2}s^{-1}$ by supplying a larger flux of antiprotons. This can be accomplished by providing longitudinal emittance decrements in the Recycler of 200 eVs/h or higher. This paper describes the electron cooling system design as well as the status of the Fermilab electron cooling R&D program.

1 COOLING SCENARIO

In all scenarios of the possible Tevatron upgrades, luminosity is essentially proportional to the number of stored antiprotons. The role of the Recycler ring is to provide more antiprotons by using it as a high-reliability post-accumulator, receiving recycled antiprotons from the previous collider store as well as antiprotons from the Accumulator.

The missions of any cooling system in the Recycler ring are:

- Transverse and longitudinal emittances of the recycled antiprotons need to be reduced by a factor of 2-3 in the 6-7 hour store length.
- Momentum spread of stacked antiprotons needs to be reduced between transfers from the Accumulator to the Recycler.
- Cooling system needs to counteract heating due to intra-beam scattering in the longitudinal plane.

Initial emittances of the recycled antiprotons might be too large to be effectively cooled with electrons. Since the Recycler ring will initially start operation with a stochastic cooling system, a hybrid system with initial transverse stochastic cooling followed by electron cooling for the final stack has many attractive features.

Table 1 summarizes the parameters of the electron cooling system that could lead to a luminosity increase by a factor of two compared to the Run II projection. The following assumptions about the antiproton stacking were used to generate this table: (1) 2-3x10^{12} of recycled antiprotons, (2) 4x10^{11}/hr antiproton flux from the Accumulator with transfers to the Recycler every 30 minutes, and (3) antiprotons are stochasticly precooled in the Recycler for one hour prior to the electron cooling to decrease the transverse emittance by a factor of three. Besides the electron cooling, there are several additional upgrades needed to realize the luminosity gain which the electron cooling offers. Because the scale and necessary development for these are rather modest, it is likely that they can be carried out as typical activities within the appropriate Fermilab departments.

Table 1: Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Relative Losses	$1\text{-}2\cdot10^{-5}$	
Cathode Diameter	5	mm
Gun Solenoid Field	200	G
Anode Voltage	≤ 50	kV
Collector Voltage	5	kV
Cooling Section		
Length	20	m
Solenoid Field	≤ 50	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	≤ 80	μrad
Antiproton β-function	20	m

2 ELECTRON BEAM RECIRCULATION

Electron cooling of the 8 GeV antiprotons in the Recycler ring requires high-quality dc electron beam with the current of several hundred mA and kinetic energy of 4.3 MeV. The only technically feasible way to attain such high electron currents is through beam recirculation (charge recovery). The recirculation principle is shown schematically in Figure 1.

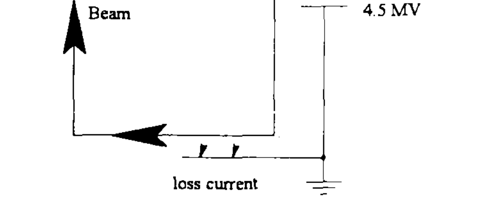

Figure 1: Simplified electrical schematic of the electron recirculation system.

The primary current path is from the cathode at high voltage terminal potential to ground where the electron beam interacts with the antiproton beam and cooling takes place, then to the collector located in the terminal, and finally through the collector power supply back to the cathode. Thus, providing there is no current loss to ground, if the terminal potential were 5 MV, the collector power supply voltage 5 kV, and the beam current 500 mA, only 2.5 kW (the beam current times the collector supply voltage) would be needed to recirculate the beam even though the *reactive* power would be 2.5 MW.

One of the principal goals of the R&D program started in 1995 is to develop and demonstrate the technology to recirculate a suitable electron beam. The technical goal set for a proof-of-principle demonstration using mostly existing equipment was recirculation of 200 mA beam for the period of one hour. This goal was reached in June 1998[4]: currents of 200 mA were maintained for periods of one hour (typical) without a single breakdown, 300 mA for 30 minutes, and 500 mA for 2 minutes. Although the recirculation tests used a 1-1.5 MeV electron beam and the Recycler electron cooling system requires a 4.3 MeV beam, the demonstration is relevant because the increased energy does not involve fundamental changes in technology.

This demonstration was performed using a 2 MeV Pelletron accelerator (Van de Graaff type) at National Electrostatics Corporation. The results of these tests support the feasibility of a Pelletron-based dc recirculating system capable of producing hundreds of milliamperes in the MeV energy range.

3 ELECTRON BEAM TRANSPORT

Traditional electron cooling devices employ a continuous homogeneous longitudinal magnetic field in the kilogauss range for the beam transport through the cooling region. One of the main reasons is to suppress the transverse velocities arising from the electron beam space charge. In the Recycler system, the space charge effects are much lower because of the higher beam energy. Thus, the longitudinal magnetic field value can be much smaller allowing for a non-traditional transport scheme. Also, the choice of a standard Pelletron accelerator prohibits us from immersing the electron beam line into a continuous magnetic field. Our transport scheme assumes a homogenous longitudinal magnetic field in the gun, collector, and in the cooling section, but a lumped focusing system in between. Consider the feasibility of this scheme for the simplest axially symmetric case: an electron is emitted along a field line in a solenoid, exits this solenoid, travels through a system of lenses and accelerating tubes, and enters into the second solenoid. The question is how to provide a low transverse velocity in the second solenoid? The axial symmetry gives conservation of a particle's generalized angular momentum, which can be written as the Busch theorem:

$$P_\theta(z)r = \frac{e}{2\pi c}\left[\Psi_0 - \Psi(z)\right], \qquad (1)$$

where P_θ is the azimuthal momentum, z is the particle's coordinate, r is the radius of the electron trajectory, c is the speed of light, Ψ and Ψ_0 are the magnetic fluxes at the point considered and at the cathode respectively. The azimuthal velocity at the cathode is assumed to be cancel. The theorem dictates that the radial position of an electron determines its azimuthal momentum. Therefore, it is sufficient to inject the electron on the proper radius in the second solenoid (where $\Psi = \Psi_0$) to zero the azimuthal component of velocity. If the electron trajectory has a zero radial slope near the second solenoid entrance, the electron will travel along the field line without a transverse velocity. A system that provides simultaneously specific values of both radius and radial slope at the point of the entrance can consist of two lenses. Simulation results for such a system are shown in Figure 2. The second solenoid in this simulation is placed immediately downstream of the acceleration tube. This simulation was performed using the SAM computer code [5].

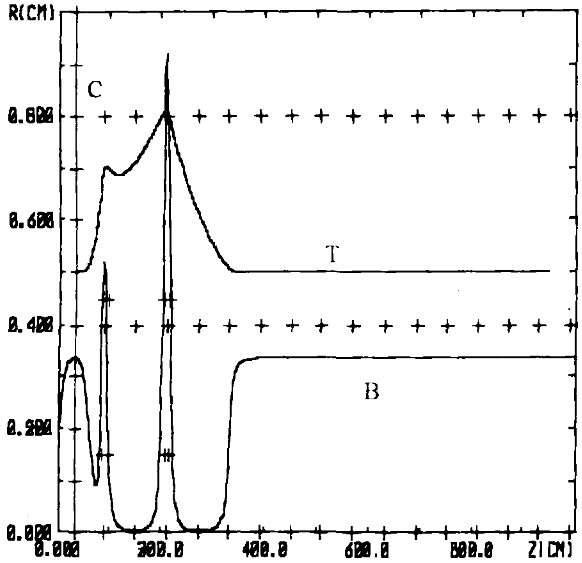

Figure 2: Single particle trajectory simulation. Curve **B** is the magnetic field distribution on the axis (600 G full scale), curve **T** is the electron trajectory, and line **C** is the cathode surface. Uniform electric field of 15 kV/cm is used to simulate a 4.5 MV accelerating tube.

The length of the first (gun) solenoid is determined by the following considerations. First of all, the beam size must be kept significantly smaller than the tube aperture. When a particle exits the first solenoid ($\Psi \ll \Psi_0$), it moves with a constant transverse momentum P_t. If the radial velocity inside the solenoid is zero, the value of P_t is equal to the azimuthal momentum, determined by the Busch theorem

$$P_t = \frac{e}{2\pi c r_s}\Psi_0 , \qquad (2)$$

where r_s is the trajectory radius at the solenoid exit. The beam expansion after the solenoid exit is determined by the ratio of P_t to the full momentum P:

$$r = \left[r_s^2 + \left(\int_{z_s}^{z} \frac{P_t}{P} dz \right)^2 \right]^{1/2} , \qquad (3)$$

where z_s is the coordinate of the solenoid exit. The P_t value is practically fixed because the value of Ψ_O is equal to the flux through the beam cross-section in the cooling section. The only possibility to decrease the beam size is to keep the accelerating electrons immersed in the magnetic field up to high enough energy. On the other hand, the higher this energy is, the larger the potential difference ΔU_s is between the solenoid and acceleration tube electrodes inside and the high voltage insulation problems become more complicated. The arrangement shown in Figure 2 is a compromise between these restrictions; the potential difference $\Delta U_s \approx 500$ kV.

The variation of the magnetic field along the axis gives a possibility of aberrations. This means that only one trajectory can have a strictly zero value of the transverse velocity in the second solenoid for a specific setting of the focusing lenses but the momentum of all other particles has a non-zero angle with respect to the beam axis. These angles, found by the simulation using the geometry of Figure 2, are shown in Figure 3 as a function of the trajectory radius. They are significantly lower that those caused by the thermal velocities (60 μrad).

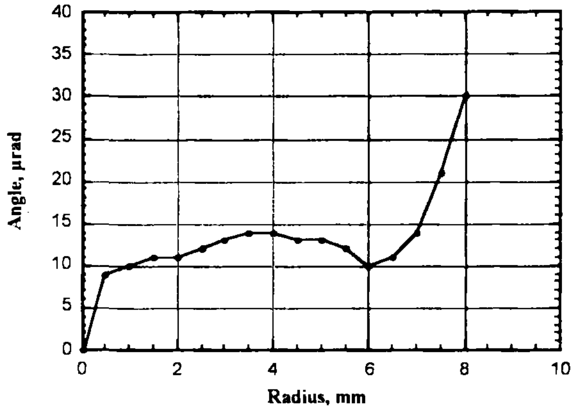

Figure 3: Angle between the trajectory and the axis as function of radius. Focusing is optimized for the trajectory with $r \approx 6$ mm.

The choice of the longitudinal magnetic field value in the cooling section is determined by three requirements:

1. Electron beam divergence due to the drift velocities should be smaller than 80 μrad.
2. Focusing provided by the longitudinal magnetic field should be sufficient to suppress electron beam instability due to the beam-wall interaction and other weaker instabilities.
3. Magnetic field flux through the beam cross-section in the cooling straight has to be equal to the magnetic flux through the gun cathode.

The following estimate can be written for the beam angular spread, θ, determined by the drift velocities in the combination of the longitudinal magnetic field, H, and the electric field associated with the beam space charge:

$$\theta \approx \frac{2I}{\beta^2 \gamma^2 Hac} , \qquad (4)$$

where I is the electron beam current, a is the beam radius, and γ and β are the usual relativistic symbols. For the electron beam parameters given in Table 1 one needs longitudinal magnetic field of at least 25 G to keep the beam divergence below the 80 μrad needed for optimal cooling. A field value of greater than 30 G satisfies this requirement. The second item in this list can be summarized by the following expression:

$$H > \frac{2\gamma\beta mc^2}{e} \sqrt{\frac{2\pi r_e n a^2}{\gamma\beta^2 b^2}} \approx 16\ \mathrm{G} \cdot \sqrt{\frac{I}{0.5\ \mathrm{A}}} , \qquad (4)$$

where r_e is the classical electron radius, b is the vacuum chamber radius (5 cm), and n is the electron density. The third requirement puts a practical limit on the longitudinal magnetic field value: if one has a 5 mm diameter cathode and 200 G field at the cathode, the value of the field in the cooling section is 50 G for a 5 mm radius beam. The field of 200 G at the cathode seems practically feasible and, therefore, the choice of 50 G field in the cooling section satisfies all three conditions.

CONCLUSION

Based on the results of our experimental and theoretical studies all the technical components of the Recycler electron cooling system are found to be feasible. Although the electron beam transport scheme seems clear in its fundamental features, extended simulations and experimental verification of this scheme must be performed.

The next step in the R&D program at Fermilab is to build a development system that differs only little from the final electron cooling system. The final adjustment to the beam can be made only with the electron cooling process itself, but the electron beam parameters appropriate for the cooling can be reached first with the development system.

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