# ENHANCING TRAPPABLE ANTIPROTON POPULATIONS THROUGH AN INDUCTION UNIT FOLLOWED BY FRICTIONAL COOLING

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*Abstract*

The antiproton decelerator (AD) at CERN currently delivers antiprotons for antimatter trapping experiments. The AD slows the antiprotons down to $\sim 5$ MeV. This energy is currently too high for direct trapping, and foils are used to slow down the antiprotons to energies which can then be trapped. This is an inefficient process. CERN is developing a new machine (ELENA) for further deceleration to $\sim 100$ keV using a decelerating ring with elecron cooling. We describe a frictional cooling scheme that can serve to provide significantly improved trapping efficiency, either directly from the AD or using a standard deceleration mechanism (induction linac or RFQ), in a short time scale and at reasonable cost which could serve in the interim until ELENA is ready for operation. Simulations provide a preliminary assessment of the concept's strengths and limitations, and highlight important areas for experimental studies. We show that the frictional cooling scheme can provide a similar energy spectrum to that of ELENA, but with higher transverse angles.

## INTRODUCTION

Sources of low-energy antiprotons are in increasing demand for for various experimental initiatives, including direct measurements of charge-to-mass ratios and production and trapping of antihydrogen, and eventually may lead to measurements of trapped neutral antimatter that test the Weak Equivalence Principle and CPT invariance [1, 2, 3].

The primary source of low-energy antiprotons remains the Antiproton Decelerator (AD) at CERN. Experiments typically suffer from low capture efficiency, because the antiprotons exit the AD at energies around 5.3 MeV, far above achievable electrostatic trap depths. To trap the antiprotons, the beam is first sent through a degrading foil which slows the particles on average but leads to large particle losses and energy spread due to straggling effects, so only a small fraction of the antiproton source are trapped.

To improve trapping efficiencies, the Extra Low ENergy Antiproton (ELENA) upgrade [4, 5, 6] to the AD has been proposed, which would use a post-decelerator and ring-based electron cooling to provide a source of 100 keV antiprotons while maintaining high phase space density. Other laboratories are also proposing low-energy antiproton deceleration and cooling rings, such as the Facility for Antiproton and Ion Research (FLAIR) [7] at GSI.

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Here we propose a simple scheme for longitudinal slowing and cooling of the antiproton beam delivered by the AD, utilizing an optional deceleration section which could be an induction linac or RF quadrupole (RFQ), followed by a degrading foil and finally frictional cooling. The frictional cooling stage consists of a series of thin carbon foils separated by re-accelerating electrostatic gradients. Such a scheme is not as effective as ELENA will be, but is an adequate and available option for antiproton experiments. Longitudinal losses should be comparable to that of ELENA, but there may be significant transverse losses even with large solenoidal fields for focusing the beam.

After providing a brief overview of our cooling concept, we present preliminary results from Monte Carlo simulations, suggesting that frictional cooling can enhance the population of trapped antiprotons by a factor of 10 or more. Potentially, a factor of 100 gain can be achieved if the frictional cooling is augmented by using an RFQ. We conclude with a discussion of advantages and limitations of the scheme, and of future directions for study.

## OVERVIEW OF FRICTIONAL COOLING FOR ANTIPROTONS

Frictional cooling has been proposed and studied theoretically and experimentally in the context of muons [8, 9, 10]. For antiprotons, frictional cooling might be used to compensate for the large mismatch between the average kinetic energy of the antiproton beam exiting the AD and the kinetic energy of particles that can be trapped — several MeV versus several keV. To compress its energy spread, each antiproton bunch is passed through a series of thin foils separated by electrostatic potential differences that reaccelerate the beam, as shown schematically in Figure 1. For antiprotons with kinetic energy below $\sim 90$ keV, higher energy particles lose more energy in each foil, so this design causes particles to converge to an equilibrium energy; this is analogous to "terminal velocity" for falling objects in air. Transverse angles reach an equilibrium of order of a fraction of a radian, and solenoidal fields are used to minimize growth in transverse spot size.

Because the stopping power starts to decrease for kinetic energies above $\sim 90$ keV, the maximum energy acceptance of the frictional cooling section is limited to the energy, typically around 400 keV, where the stopping power drops back down to match that of the equilibrium energy. Thus a degrading foil [11] must still be used, whose thickness is comparable to the range of the incident antiprotons. If the incident antiprotons have an energy of $\sim 5$ MeV, straggling

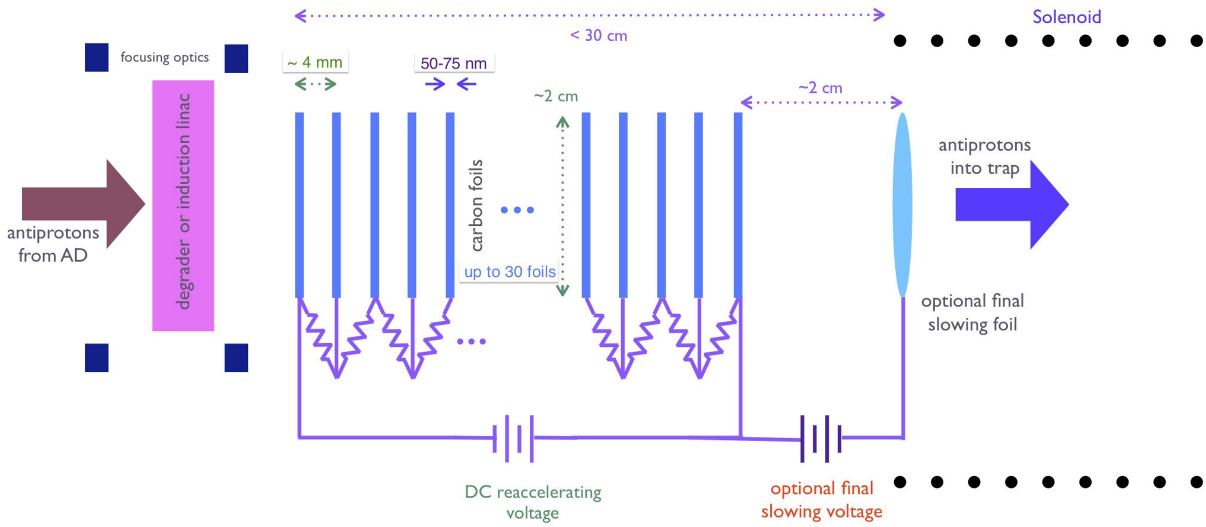


Figure 1: Schematic of the proposed frictional cooling system. The diagram is *not* drawn to scale, but is intended to illustrate the major components. Because the antiproton current is small and therefore the power requirements modest, a resistor chain can be used to divide a single high voltage source.

will lead to a broad initial energy distribution with a small fraction in the acceptance range for trapping. Decelerating the antiprotons to $\sim$ 100 keV before the foil leads to straggling effects only of order 1 keV.

Performance is limited by particle losses, straggling, and multiple scattering. The impact of multiple scattering grows worse at lower energies. To control the effects of multiple scattering in the foils, we choose to use carbon foils as a convenient low-Z option, and the equilibrium energy of the beam is set to be higher than the typical acceptance of traps. To compensate for this, the very last foil will be thicker than the others in order to optimize the trapping efficiency. The number of foils, their thickness, and the potential differences between them are chosen to effect the desired cooling using currently available thin foil technologies while keeping the overall length of the device and the total voltage drop within reasonable bounds.

## DECELERATION SCHEMES

Following the AD, we consider four ideas for deceleration including the ELENA proposal, an induction linac, an RFQ, or a simple foil. Every scheme, including ELENA, will require some degrading foil to further reduce energy. Note that the optimal choice for a degrading foil going directly into a trap may be different from that of a foil going into a frictional cooling section. The deceleration options are quite conventional and well studied. Degrading foils are modeled using the same physics as for frictional cooling.

The AD [12] delivers about $2\times10^7$ antiprotons per bunch of about 0.3 $\mu$s duration at a mean kinetic energy of 5.3 MeV every 1.8 minutes. The horizontal and vertical (87%) emittances are about 1 $\pi$ mm mrad and 2 $\pi$ mm mrad, respectively, and the momentum spread after cooling and re-bunching is about 0.1%, corresponding to an RMS kinetic energy spread of about 10.6 keV. Through electron cooling, ELENA can decelerate this beam to 100 keV with very small energy spread and low divergence. After the degrader, almost all of the beam is in the energy acceptance of a typical trap. An induction linac can achieve a gradient of 1 MeV/m for a long (300 ns) pulse, which can be increased if the pulse duration can be shortened from the nominal AD pulse length. However, that will negatively impact the capture efficiency. The resulting energy spread is expected to be of the order of 25 keV at 50 keV energy. An RFQ can slow the beam to $\sim$ 50 keV with an energy spread of 10 keV. Note that one current experiment at CERN, ACUSA, employs an RF quadrupole system to decelerate bunches from the AD down to about 15 keV. But following a decelerator with active cooling can greatly enhance the number of low-energy antiprotons.

## SIMULATION RESULTS

In Monte Carlo simulations, we use tabulated data for the average energy loss of particles in matter generated by the "txphysics" software package [13], which uses SRIM [14, 15] data. This allows us to use a single methodology for both the degrader and frictional cooling foils, covering a range of kinetic energies from zero up to several MeV where a variety of physical effects come into play. Antiprotons are not included in these tables, and the Barkas effect [16, 17, 18], where antiprotons experience less energy loss than protons at low energies, is estimated as a simple factor of 0.5 for the range of energies considered here. The other major effects, straggling and multiple scatter, are treated according to algebraic expressions based on experimental data [19, 20, 21] and theory [22, 23, 24]. Because multiple scatter is critical to frictional cooling performance and is not well known for antiprotons, it is parametrized according to a simplified fit of the Molière scattering cross-section to a Gaussian:

$$\frac{d}{ds}\sigma_\theta^2 = \left(\frac{13.6\,\mathrm{MeV}}{\beta cp}\right)^2 Z_p^2 \frac{\rho}{x_0}\kappa_\theta \approx \kappa_\theta\,\mu_\theta E^{-2}\frac{\rho}{\rho_0}\,, \quad (1)$$

where the second form applies in the limit of low kinetic energy. Here $x_0$ is the radiation length in units of g/cm$^2$, or 43 g/cm$^2$ for graphite, $Z_p$ is the charge of the beam particles, $\rho$ is the density, $\rho_0 = 2.21$ g/cm$^3$ is the nominal density, and $\mu_\theta \approx 2.3\times10^5$ rad$^2$eV$^2$/nm for protons in carbon. We have incorporated an additional dimensionless factor $\kappa_\theta$ to account for a variety of uncertainties: differences between protons and antiprotons, the scaling at very low velocities, and the distinctive configuration used for frictional cooling. We will consider several values of the parameter $\kappa_\theta$, but the data suggests it could be as low as 0.05 for antiprotons. Annihilation is neglected, but all stopped, backscattered, or reflected particles are treated as lost.

The frictional cooling consists of multiple foils with a thickness of 50–75 nm, separated by 4 mm gaps with a voltage per gap chosen within the range 4–5 keV. The final foil is typically double this thickness. Straggling turns out to have a very small effect on the frictional cooling section. It is important for the degrader and thus affects the input into the frictional cooler stage.

Results are given in Table 1 for antiproton cooling using various configurations and for $\kappa_\theta$ chosen to be 0.05, 0.1, or 0.25. The RFQ plus frictional cooling configuration can yield similar output to ELENA followed by a degrading foil over a range of values of the scattering rate. At increasing values of $\kappa_\theta$, more foils and higher voltage per foil are needed, requiring significantly more total voltage. For the RFQ example, the number of foils must be increased from 9 to 10 as $\kappa$ is increased from 0.05 to 0.1, also requiring the total applied voltage to increase from 40 keV to 52 keV. At even higher levels of scattering, performance begins to degrade more significantly. The kinetic energy spectrum for the RFQ example with and without frictional cooling is shown below, given in units of % of beam per 1 keV. Note that the spectrum is given in terms of total kinetic energy, while the acceptance criterion is based on longitudinal kinetic energy.

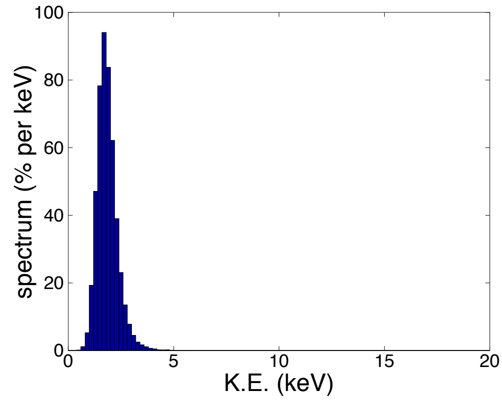


Figure 2: Antiproton spectrum from an RFQ followed by a degrader foil and a frictional cooling section for the case $\kappa_\theta = 0.05$.

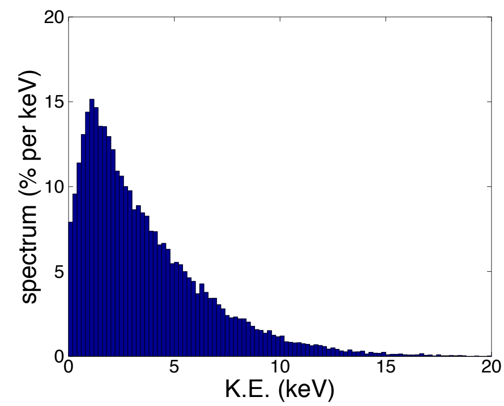


Figure 3: Antiproton spectrum from an RFQ followed by a degrader foil alone for the case $\kappa_\theta = 0.05$.

## DISCUSSION

Simulations suggest that a simple frictional scheme applied to antiproton bunches delivered by the AD can enhance the numbers of trappable particles by an order of magnitude when compared to the use of a degrading foil alone, and even more if additional upstream deceleration is employed. These simulations include some simplifying assumptions, especially as to the differences between protons and antiprotons.

Frictional cooling can reduce to keV-levels both the mean energy and energy spread of the portion of the beam that lies below some cutoff energy. Countering this will be particle losses, increases in spot size and bunch length, and a large RMS angular divergence.

The requirements for a frictional cooling section seem technologically feasible: $<$ 30 foils, each about 75 nm thick, and if necessary fitting into a compact space; a total DC voltage source of $\sim$ 50 kV up to possibly 150 kV; and a deceleration mechanism after the AD if a degrading foil by itself does not yield sufficient performance. In addition, because divergence angles become large, a strong solenoidal field may be needed, rising to $\sim$ 3 T, to provide transverse confinement. In many trapping applications the frictional cooling section can piggy-back on the existing solenoidal field.

Within the frictional cooling stage, it is multiple scattering that primarily limits performance. While the results are quite sensitive to the rates of multiple scattering, these are rather poorly known for low-energy antiprotons in carbon or other solid materials. Scattering of antiprotons is likely subject to a Barkas effect, and the observed cross-section

Table 1: Numerical results of antiprotons for different configurations and values for scattering. Only longitudinal acceptance is considered; transverse effects will further reduce the total trapping efficiency.

| **Type** | **Init E** | **Init $\sigma_{\mathbf{E}}$** | $\kappa_\theta$ | **Degrader Thickness** | **Voltage** | **# cooling foils** | **% accepted** |
|---|---|---|---|---|---|---|---|
| AD | 5 MeV | 10 keV | 0.05 | 185 $\mu$m | 0 | 0 | 1.1 |
| | | | 0.05 | 185 $\mu$m | 114 kV | 26 | 15 |
| | | | 0.10 | 185 $\mu$m | 135 kV | 26 | 14 |
| Induction Linac | 50 keV | 25 keV | 0.05 | 450 nm | 0 | 0 | 16 |
| | | | 0.05 | 250 nm | 40 kV | 9 | 67 |
| RFQ | 50 keV | 10 keV | 0.05 | 450 nm | 0 | 0 | 38 |
| | | | 0.05 | 250 nm | 40 kV | 9 | 96 |
| | | | 0.10 | 250 nm | 52 kV | 10 | 94 |
| | | | 0.25 | 250 nm | 72 kV | 12 | 80 |
| ELENA | 100 keV | 0.1 keV | 0.05 | 770 nm | 0 | 0 | 94 |
| | | | 0.10 | 760 nm | 0 | 0 | 91 |
| | | | 0.25 | 750 nm | 0 | 0 | 81 |

for low-energy protons is already adequate for frictional cooling. Better measurement of these cross-sections would help to define the achievable efficacy of and requirements for frictional cooling. Annihilation effects are expected to be small. Because of the Barkas effect, note that if such a scheme is to be tested using a proton beam, one must either use thinner foils or higher voltages between foils to see equivalent results.

Good understanding of the longitudinal and transverse phase space acceptances of the downstream trap is essential to optimize performance for specific applications. While we have considered for simplicity a repetition of identical foils and gap-voltages, tapering of these quantities might further improve performance. Optimization and improved simulation of the cooling layout, as well as more realistic modeling of the upstream deceleration and downstream trapping dynamics, are goals for future study.

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