

Physics with Ultralow-Energy Antiprotons

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Abstract

In this report I will describe the current status of the antiproton decelerator (AD) facility at CERN, and highlight the physics program with ultralow-energy antiproton at this installation. I then will comment on future possibilities provided higher-intensity antiproton beams become available at Fermilab, and review possibilities for initial experiments using direct degrading of high-energy antiprotons in material, as has been developed and proven at CERN.

1 Introduction

Low-energy antiprotons for fundamental physics experiments were first made available when the CERN antiproton source for the high-energy program in pursuit of the W -bosons was constructed. At the time it was realized that with modest additional expenses a dedicated low-energy facility could be added. As long as the antiproton source was predominantly operated for the high-energy community and LEAR was a mere “parasite” the low-energy community enjoyed a productive period, performing a variety of successful experiments in the low and medium-energy regime and continuously developing upgrades to the facility to allow new experiments. With the end of the need at CERN for antiprotons for the high-energy community this climate changed drastically, and despite a strong push from the user community, detailing an exciting physics program with low-energy antiprotons, none of the proposed programs was ever realized and ultimately LEAR was shut down in 1995. Through the diligent insistence of several members of the ultralow-energy community [1] a new source of low-energy antiprotons, the CERN antiproton decelerator (AD), was established, but it was clear from the onset that this facility was very limited in its scope and would serve only a small fraction of the user community. Therefore the search for a new facility continues and several possible options have been discussed, Fermilab, with the world’s most intense source of antiprotons, being one of the most promising candidates. As was learned from the development of the AD facility at CERN as well as from the downfall of earlier proposals to upgrade the LEAR facility to a “Super-LEAR” [2], success of such an endeavor is based on

a balanced combination of a technically sound proposal on the machine aspects (preferably having minimal impact on the operation of the main facility), a strong physics program (spanning diverse areas of physics research), and a strong user community supporting such a program. In this paper I will attempt to address some points in these areas pertinent to the lowest-energy end of the spectrum of experiments, namely those using trapped particles.

2 Low-Energy Antiprotons at CERN

Late 1996 a highly successful low-energy antiproton program conducted at the Low-Energy Antiproton Ring (LEAR) at CERN came to an end with the decommissioning of the antiproton source consisting of the Antiproton Collector (AC), the Antiproton Accumulator (AA), and the actual LEAR machine. For a detailed description of this facility see [3]. Besides providing a continuous beam of antiprotons of approximately 10^6 antiprotons/second in the momentum range $100 \text{ MeV}/c$ to $1.2 \text{ GeV}/c$, a fast extraction mode in which part or all of the LEAR beam could be extracted in a 200-ns pulse [4] had been implemented at the lowest momentum during the last 5 years of running.

The latter mode was used by 2 experiments (PS196 and PS200) to trap antiprotons in modified Penning traps [5, 6]. Antiprotons from LEAR at $105 \text{ MeV}/c$ were sent through a sequence of thin vacuum windows, radiator baffles, and a final aluminum foil (“the degrader foil”). The antiprotons lost energy through collisions with the nuclei of the traversed material and eventually, if the material was sufficiently thick, would stop and annihilate. If the total foil thickness was chosen just right to transmit 50% of the incoming antiprotons, the number of low-energy antiprotons emerging from the final degrader foil was maximized [7]. In the case of PS200, which used a trapping potential of up to 30 keV, the overall collection efficiency was of the order of a few parts in 10^3 , enabling the capture of 1 million antiprotons from a single LEAR pulse. Once captured in the trap, the antiprotons could be cooled to equilibrium with the cryogenic temperature of the apparatus (4 Kelvin is equivalent to 0.3 meV) using electron cooling. Thus this method spans 10 orders of magnitude in kinetic energy with a single, simple step. Figure 1 shows a summary of results obtained by the PS200 experimental team (note that the energy distribution shown is for particles extracted from the Penning trap and is altered by the Coulomb repulsion between the antiprotons, and does not reflect directly the much colder distribution of particles in the trap).

2.1 The antiproton decelerator

At the time of the LEAR shutdown, it was realized that a pulsed beam of antiprotons could be achieved with much simpler means based on an idea first introduced by Baird *et al.* [8]. The basic scheme consists of utilizing the original production-target setup, but then using the Antiproton Collector not only for the initial collection, but to add deceleration, stochastic-cooling, and electron-cooling capabilities to the ring as well. This allows the use of just one ring instead of the three machines (and associated beam transfer lines) required in the LEAR era. A preliminary feasibility study [9] was initiated through the CERN/PS division, and it was found that this new approach would reduce the operating cost of the

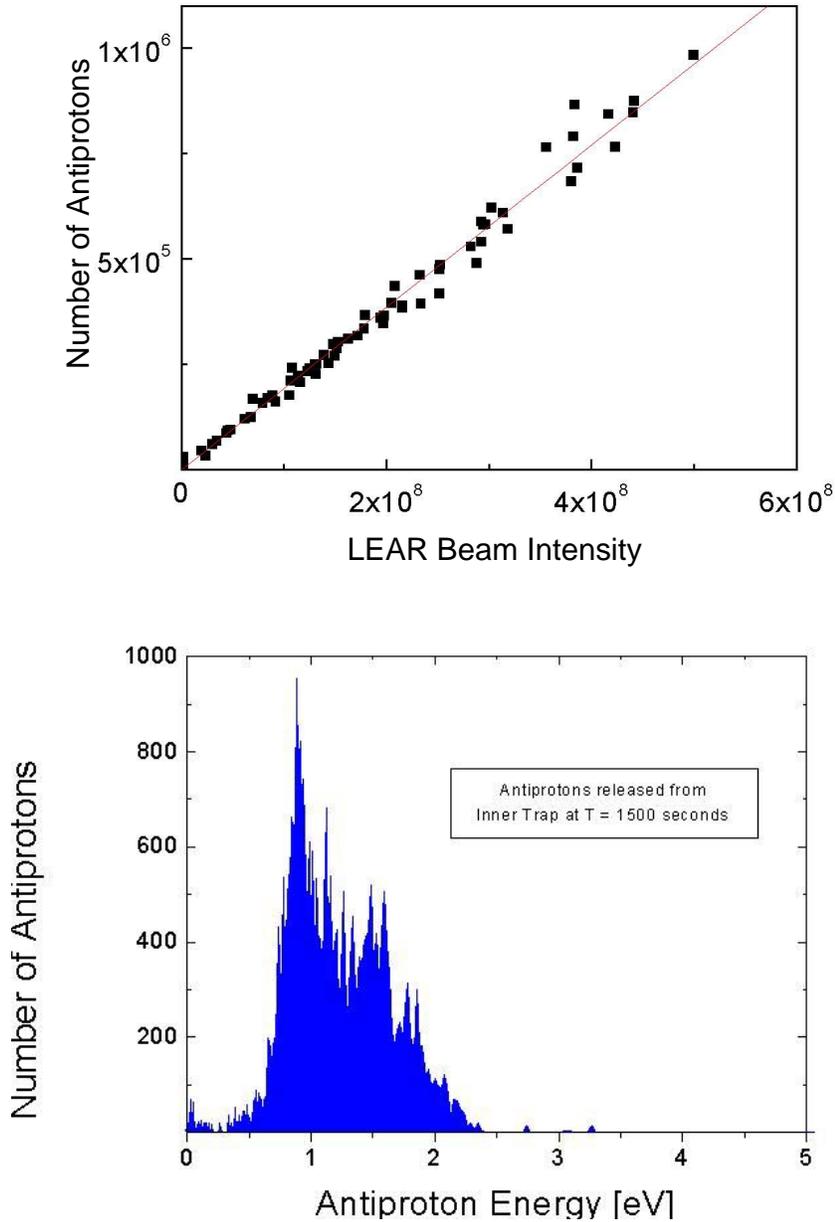


Figure 1: (a) Total number of antiprotons captured from LEAR vs. LEAR shot intensity, (b) Energy distribution of ejected particles

facility by an order of magnitude, without significantly reducing the integrated intensity of antiprotons available for trapping experiments. Once the technical requirements of the basic scheme were understood and the feasibility was proven, the user community initiated discussions with the CERN management [1], detailing both the machine requirements and the physics program. Initial reactions from CERN were positive and a detailed design study

for the new project, now named AD (for Antiproton Decelerator), was undertaken [10]. A large part of the funding required for the modification of the existing facility was generated within the user community, and the final ingredient necessary for an unconditional green light by the CERN management, a compelling physics program, was spelled out in several letters of intent [11].

2.1.1 Machine design and performance

The CERN Antiproton Decelerator (AD), which came on-line in November 1999 and delivered first antiprotons for physics experiments in April 2000, is shown schematically in figure 2. Antiprotons from the production target are injected at a momentum of $3.5 \text{ GeV}/c$ and then cooled and decelerated to $100 \text{ MeV}/c$ (5.3 MeV kinetic energy) and finally ejected to one of the experimental areas. The machine uses the pre-existing antiproton-production target area and equipment, and is an adaptation of the Antiproton Collector (AC) Ring from the LEAR era. Figure 3 shows the deceleration cycle of the AD, and table 1 shows the beam parameters at each momentum stage, the time spent at each stage, and the cooling mechanism applied, as projected in the design study. These design values have essentially been matched by the AD team with the exception of longer time periods needed for the individual steps, setting the current repetition rate to roughly 1 pulse every 3 minutes [12].

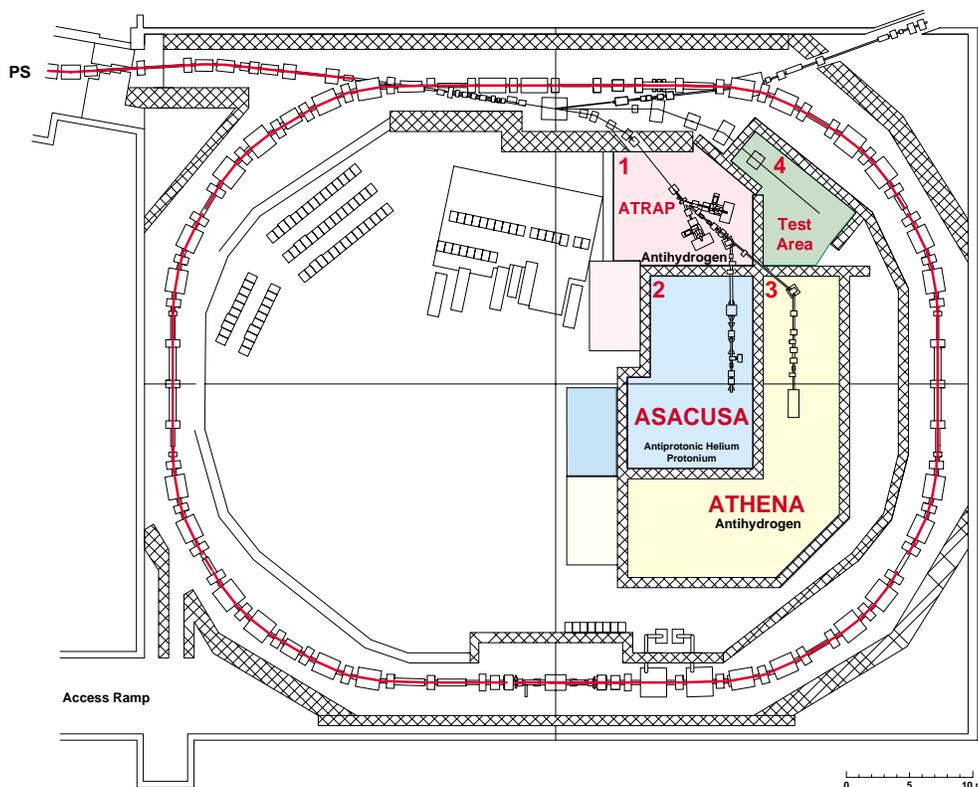


Figure 2: Overview of the AD facility at CERN (from [10]).

p	ε_i	ε_f	$\frac{\Delta p}{p_i}$	$\frac{\Delta p}{p_f}$	t	
[GeV/c]	[π mm mrad]		[%]		[s]	
3.5	200	5	1.5	0.1	20	STOCHASTIC
2.0	9	5	0.18	0.03	15	COOLING
0.3	33	2	0.2	0.1	6	ELECTRON
0.1	6	1	0.3	0.01	1	COOLING

Table 1: Transverse emittance and momentum spread before (i) and after (f) cooling, and cooling times [10].

The antiproton momentum is lowered in two stages from 3.57 GeV/c to 0.3 GeV/c, followed by stochastic cooling after each stage to reduce the momentum bite. At 0.3 GeV/c the antiproton speed is low enough for electron cooling (which is more rapid than stochastic cooling) to be applied, and this is also done following final deceleration, just prior to extraction, at 0.1 GeV/c. The entire cycle currently takes around 200 seconds and is capable of delivering around 5×10^7 antiprotons in a pulse of 500 ns duration. An option for stacking up to ten bunches of antiprotons at 3.57 GeV/c in the AD has been described [10] but not yet implemented. This, if effected, would ease the stacking requirements for the Penning trap experiments and may mean that upwards of 10^6 antiprotons can be captured in an appropriately designed trap from a single AD shot.

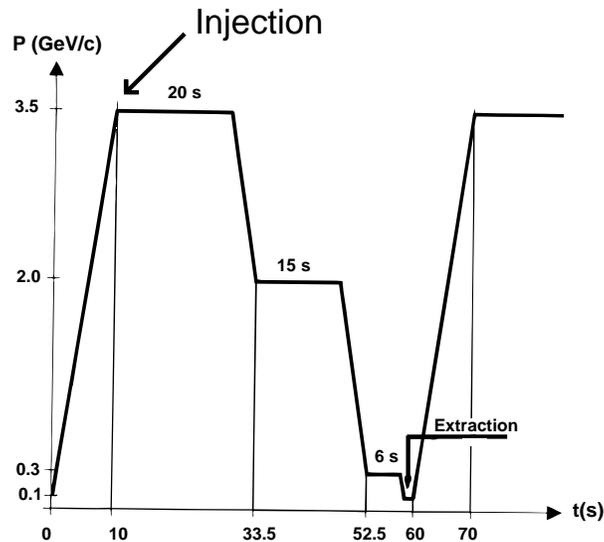


Figure 3: Machine cycle for the AD operation (from [10]).

It should be noted that the facility is designed specifically for experiments using traps, *i.e.* neither in-beam experiments nor slow extraction of antiprotons is foreseen. Additionally, to avoid construction of new experimental facilities, all experiments occupy space in the center of the AD ring and most of the available real estate is occupied by the three approved

experiments (the floor space in the lower-left quadrant of the hall – see figure 2 – is needed for transporting equipment and supplies to and from the experiments) and little space for expansion is available.

2.1.2 *The physics program at the AD*

The main emphasis of the physics program at the AD is on the production and spectroscopy of antihydrogen at rest. With the extreme high precision achieved in spectroscopy of hydrogen over the last decades [13] it is natural to assume that a direct comparison of antihydrogen to hydrogen should yield the ultimate test of CPT symmetry. In general this is true, but a more careful analysis is necessary to establish which of several specific measurements proposed has the highest sensitivity to possible violations of CPT. In the context of a minimal extension of the Standard Model and Quantum Electrodynamics Alan Kostelecky and collaborators from Indiana University have analyzed this problem [14]. Using the example of the anomalous magnetic moment, it was shown that traditional figures of merit could be misleading and a new, universal, description was used to analyze both the charge-to-mass-ratio comparison and the measurements of the magnetic moments of antiprotons and protons for their sensitivity to CPT-violating effects [15].

The highest-precision comparison between protons and antiprotons is for the measurement of their cyclotron frequencies, *i.e.* the charge-to-mass ratios for both particles. However, within the theoretical framework considered by the authors the cyclotron frequencies for proton and antiproton are independent of CPT-violating quantities and this comparison does not give a direct bound on CPT violation. In contrast, a comparison of the magnetic moments of the antiproton and the proton with the same precision as performed for electrons and positrons could yield a bound on CPT violation of 1 part in 10^{23} , providing a particularly stringent bound on CPT violation in the baryon sector. Such an experiment has been proposed [16] and should be an important part of the future program of low-energy antiproton physics, either at the AD or at another facility. For experiments with antihydrogen it was observed that, at least within the theoretical framework of this discussion, the 1S-2S energy difference is insensitive to violations of CPT in first order, while the hyperfine structure of antihydrogen is affected directly [17].

But the conclusion that a measurement of the hyperfine structure should be pursued rather than a precision measurement of the 1S-2S transition is premature, since it is based on the naive assumption that a precision identical to the one in the hydrogen case could be reached. Before one can discuss a high-precision comparison of hydrogen and antihydrogen one needs to examine the experimental methods and requirements used in the different experiments on hydrogen spectroscopy. The highest precision so far was achieved in experiments to study the 1S-2S level difference using cold beams of hydrogen atoms [13] and the measurement of the ground-state hyperfine structure which was performed using a hydrogen maser relying on wall collisions [18]. The experimental approaches of these experiments are not directly applicable to the study of antihydrogen and new experimental methods will need to be developed. Lacking efficient means to cool antihydrogen atoms at this time (albeit a weak CW Lyman- α laser has been developed [19] and theoretical work considering collisional

cooling of antihydrogen atoms has been performed [20]) one of the fundamental requirements to allow high-precision experiments is the direct formation of antihydrogen atoms at very low energy. Another is the accumulation and storage of antihydrogen atoms in a neutral-atom trap to compensate for the low number of antiatoms available.

Two experiments pursuing these goals have been proposed for the AD program and are in the early stages of preparation at this time. Both the ATHENA [21] and the ATRAP [22] collaborations plan to capture antiprotons from the AD beam using the foil degrading method developed at LEAR, and then to cool the antiprotons, once captured, using electron cooling. Initial test runs at the AD have shown capture efficiencies of the order of 1 part in 10^3 in agreement with theoretical expectations for this process [23].

Once cold, the antiprotons will be allowed to interact with a dense plasma of positrons to form antihydrogen via radiative recombination (RR), possibly enhanced by laser radiation (SRR), or via three-body recombination (TBR), a process which theoretically dominates at lower temperatures and higher positron densities (but has not yet been demonstrated in experiments with ultracold merged beams [24]). While both radiative recombination and stimulated radiative recombination lead directly to low-lying atomic states of the produced antiatoms, three-body recombination predominantly yields highly excited Rydberg states which may auto-ionize in the electric fields present in the charged-particle traps if they are not pumped down to more stable levels at a fast rate.

All processes to form antihydrogen depend strongly on the density of the positron plasma seen by the antiprotons, and many more positrons than antiprotons are needed to convert all antiprotons into antihydrogen in a reasonable time period. In both experiments positrons for the production of antihydrogen are obtained from radioactive decay of a β -emitting source (^{22}Na). The fast positrons emitted by the source are implanted in a thin tungsten foil, where they lose energy through collisions with the bulk, and thermalize. A fraction of the positrons can diffuse back to the surface of the tungsten, from where they may be emitted as epithermal positrons with a few eV of kinetic energy before they can annihilate.

ATHENA plans to collect the positron plasma using an accumulation scheme based on further slowing down of the moderated positrons from the radioactive source using inelastic collisions in a buffer gas, following the development by the group of C. Surko at UCSD [25]. It is foreseen to collect 10^7 to 10^8 positrons in approximately 2 minutes from a 15 mCi ^{22}Na source in a Penning-Malmberg trap [26], which will subsequently be transferred from the positron accumulator to the main ATHENA apparatus [27].

ATRAP has developed a novel accumulation scheme which yields low-energy positrons directly inside the cryogenic vacuum section of the apparatus. A significant fraction of the slow positrons emitted from the surface of the tungsten degrader are accompanied by slow electrons. Due to the strong magnetic field these two particles form a quasi-bound state, and, if the Coulomb interaction between the particles exceeds their kinetic energy, a highly magnetized Rydberg state of positronium is formed. This state is then ionized by the electric field present in the Penning trap, and either the electron or the positron can be trapped, dependent on the sign of the potentials applied to the trap electrodes, if the kinetic energy is below the well depth. The accumulation rate achieved in this manner is orders

of magnitude higher than that obtained by electronically damping the energy of low-energy positrons passing through the trap. Initially accumulation rates of 1 million positrons in 15 hours were reported [28] but more recently rates as high as 2 million positrons per hour have been achieved [29].

Both experimental groups currently concentrate on the formation and identification of antihydrogen atoms with the actual trapping and spectroscopic studies of antihydrogen foreseen for the second phase of the experimental program.

The primary (short-term) goal of the third experimental group formed around the AD facility, ASACUSA [30] (which stands for “Atomic Spectroscopy and Collisions Using Slow Antiprotons”) is the continuation of studies of antiprotonic helium which had been started in the last years of the LEAR program [31]. The LEAR antiprotonic-helium experiments, in which laser beams were used to induce quantum jumps of the antiproton from one orbit to another, revealed that this unusual atom constitutes an extremely powerful microscope through which the antiproton can be studied in minute detail. The story began in 1991 at the KEK laboratory near Tokyo, where a Japanese team was following up an earlier observation that K^- mesons stopped in liquid helium took a longer time to be absorbed by the helium nucleus than expected. Repeating these measurements with antiprotons, they measured the elapsed time between the introduction of these particles into a liquid-helium target and their subsequent annihilation. In about 3% of the cases, they found an average value of the order of $3 \mu s$ – for the remaining 97% it was about one picosecond, the value that had been confidently predicted for many years. Closer inspection at LEAR then showed that the longevity of the antiprotons could be attributed to the formation of a metastable (*i.e.* long-lived) form of the antiprotonic helium atom.

The properties of any atom are determined by the properties of its constituent particles. It is the extremely long lifetime (in atomic terms) of these antiproton-containing helium atoms that permits their properties to be measured at high precision by the powerful and accurate tools of laser spectroscopy, and thereby gives them a test-bench role for studying the antiproton itself. Already at LEAR the wavelengths of certain spectroscopic lines were measured to a few parts in ten million, permitting the antiproton charge and mass to be deduced with similar precision. Some of the LEAR results were reproduced at the AD within hours of delivering its first antiprotons and more recently new atomic lines were measured using double-resonance spectroscopic methods [32]. Future goals of this group include studies of atomic collisions in dilute targets and also the production of antihydrogen atoms, possibly in flight, for a study of the hyperfine structure. For this purpose the ASACUSA collaboration is studying a different, possibly much more efficient, approach to obtaining keV antiprotons, a radio-frequency quadrupole (RFQ) decelerator [33].

Laser spectroscopy of antihydrogen can in principle be performed on a small sample of stored atoms, possibly even with a single atom when shelving methods as those developed for single-ion spectroscopy [34] are used. Those experiments are well suited for the parameters of the AD facility. Other experiments, requiring a continuous supply of low-energy antiprotons, specifically the study of the hyperfine structure of antihydrogen in an atomic-beam apparatus [35] or the measurement of the interaction of antihydrogen atoms with the gravitational field of the Earth using atom interferometry with matter gratings [36], would strongly benefit

from a higher-intensity antiproton source.

3 Trapping of Antiprotons from the Fermilab Antiproton Source

Fermilab has been one of the prime candidates for a high-intensity antiproton source for many years. Fermilab currently has an antiproton production rate of 4×10^{11} antiprotons per day and a maximum stack intensity of 2×10^{12} . In principle one could consider using the entire stack for a single trapping experiment, but more commonly it is discussed to extract antiprotons in bunches of 2×10^{10} particles each at a repetition rate of one pulse every few minutes. While future options considered include a dedicated storage ring for 2×10^{10} antiprotons at 100 MeV/ c , for the near-term future it is of interest to study the possibility to directly degrade and capture the antiprotons from the Main Injector ring after decelerating the antiproton stack in the Main Injector to the lowest possible momentum. While it is generally assumed that this momentum is limited to 2 GeV/ c , there is hope, and I will give strong arguments for the benefit of attempting this, to reach 1 GeV/ c , especially since the antiprotons would be ejected immediately after deceleration and no long-term stability of the beam would be required at the lowest momentum. Naturally the price to pay for choosing such a simple method (compared to dedicated deceleration rings or RFQ systems) will be a low efficiency. But with the high initial intensity available, it still seems possible to achieve with minimal technical overhead, numbers of trapped antiprotons interesting for fundamental physics and for some proof-of-principle tests for possible applications of low-energy antiprotons.

3.1 The AD test case

The overall efficiency of the degrading process is very sensitive to the choice of the material, the exact thickness, and also the placement (in case of a distributed degrading system) of the individual components of the degrading system. Since the range for tuning the degrading stack on line is limited, it is necessary to perform accurate simulations of the process as a basis for the experimental design. A good guide for the calculations of expected efficiency is the work performed for experiments at LEAR and AD [37]. Two program packages are available for this, SRIM2000 (a successor of the original TRIM code) [38] and GEANT [39]. Both codes use a Monte Carlo routine to model the energy loss of particles in matter, with GEANT additionally being capable of generating trajectories of the particles outside the material, including effects of external electric and magnetic fields. Both codes rely on empirical data for cross sections of the various energy-loss processes considered, which turns out to be a weakness especially at the lower energies of interest for trapping, where such data are not readily available. Nevertheless, reliable results can be obtained by carefully monitoring the input characteristics and correcting for the known systematic uncertainties at lower energy. As an example displaying the predictive power of these calculations I will first give a brief description of the calculations performed for the degrading and capture tests of the ATHENA collaboration and compare the results of various calculations with the experiment.

At the AD, an antiproton pulse is sent to the ATHENA experiment at a momentum of $100 \text{ MeV}/c$, equivalent to a kinetic energy of 5.3 MeV . These particles traverse an initial rotatable aluminum foil for fine adjustment of the degrading stack, a $67 \mu\text{m}$ silicon beam monitor, a $25 \mu\text{m}$ stainless steel vacuum isolation window, and the final degrader consisting of a $70 \mu\text{m}$ aluminum foil, which serves also as the high-voltage entrance electrode of the capture trap. Both GEANT and SRIM were used to calculate the optimum thickness for the final degrader foil. Results obtained for the optimum thickness of the rotatable foil for the two codes were $40 \mu\text{m}$ and $65 \mu\text{m}$ respectively. The difference between the two codes may most likely be attributed to the difference in the data sets for the energy loss cross sections used by the programs. SRIM does not contain any information about the difference in stopping power for antiprotons *vs.* protons, the so-called Barkas effect [40]. Antiprotons appear to have a higher effective energy than protons, which was taken into account in our calculations by increasing the input value for the kinetic energy of the antiprotons from 5.3 MeV to 5.5 MeV , following results obtained by the PS196 collaboration at LEAR [41]. The version 3.0 of GEANT used for these calculations [37] included the latest data set on degrading power for antiprotons at low energies from the collaboration [42] and no energy correction was applied here. Still, it must be noted that the low-energy cutoff for most processes in GEANT3 is around 10 keV .

To allow for the systematic shift between the two results it was decided to perform the initial test runs with the final degrading-foil thickness of $70 \mu\text{m}$ and to add a rotatable foil before the silicon detector to increase the total thickness continuously over some range. In figure 4 the results of the first test runs are shown, giving the total thickness of aluminum needed for optimum degrading as $114 \mu\text{m}$ (the sum of the $70 \mu\text{m}$ degrader foil and the thickness of the rotatable foil at peak efficiency). This result closely agrees with the estimate from SRIM, indicating a possible mismatch of the GEANT input data set for ultralow energies. Based on these test runs the rotatable foil has now been eliminated and the thickness of the final foil has been increased to $115 \mu\text{m}$. This reduces the radial straggling in the earlier part of the setup and improves the beam quality at the final foil, thereby increasing the efficiency for capture into the specific trap design by a factor of 3 – 4.

3.2 The Fermilab scenario

The same calculations can be performed for parameters viable at Fermilab. W. Kells studied this problem in 1989 [43], and summarized his findings for incoming beam momenta of 0.7 , 1 , and $2 \text{ GeV}/c$ and three different degrader materials (Be, Pb, and Os). He showed clearly that in terms of multiple scattering and resulting output beam-spot size, osmium is the best choice amongst these materials. He used the program TRIM86 [38] to calculate the energy loss of high-energy antiprotons in the degrading material and to arrive at the number of antiprotons below a given energy threshold to emerge from the degrading block (given the required thickness, the expression degrading foil would be rather inadequate). To arrive at the final column of Table 1 in his paper for the number of particles trapped per mA of incident beam, he applied two corrections to the raw data obtained. Since the needed degrading stack thickness at higher energies becomes significantly larger than a nuclear interaction length, and TRIM does not include any losses due to nuclear effects, an exponential attenuation of

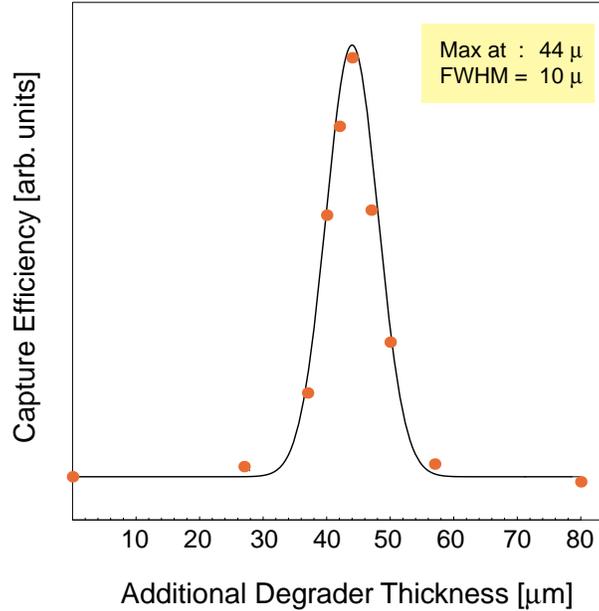


Figure 4: Degrading efficiency *vs.* additional degrader thickness in ATHENA test runs.

the beam intensity due to nuclear absorption was added. Secondly, Kells only considered particles within a 1-cm-diameter spot to be trappable. The latter restriction may be lifted by proper trap design or by using a distributed degrading stack with intermediate focusing of the beam, so I shall ignore this factor in the following discussions.

For the present study I used the successor of the original TRIM code, SRIM2000 [38], and an input beam momentum of both the nominal minimum momentum of the Main Injector ring of 2 GeV/ c and the desired value of 1 GeV/ c . As shown by previous studies [7], to establish the optimum degrader thickness it is sufficient to find the 50% transmission point, which can be done with good statistical accuracy using a relatively low number of incident particles (most cases were done with just 500 particles). A study of the transmission of antiprotons through a varying thickness of degrader material gives the optimum thickness for degrading a beam of momentum 1 GeV/ c as 10.9 cm and as 70.7 cm for 2 GeV/ c .

These numbers significantly disagree with the 7.35 cm and 34.1 cm respectively given by Kells, and at the time of writing this report it is not clear if the discrepancy is due to a difference in codes between TRIM86 used by Kells and SRIM2000 used here. To address this question more carefully, I ran a number of tests and found several inconsistencies in the results obtained from TRIM and SRIM which are noteworthy. First I compared TRIM96 – which is part of the SRIM2000 software package and runs under DOS – and SRIM2000 for an identical input file for 1 GeV/ c and found a 10% difference in optimum degrading thickness, with SRIM2000 asking for a larger thickness. Also, with the final layer being the degrading foil in which particles range out, a significant number of particles were recorded as transmitted with 0 eV energy. To eliminate this effect I added an additional layer of vacuum (actually, I chose He gas at a density of 2×10^{-7} g/cm²). This layer had no significant

effect on the energy of the transmitted particles but effectively decoupled effects near the final surface of the degrading stack from the transmitted particles. With this method both the 0 eV ghosts were eliminated and a better definition for the exiting beam spot size was obtained. Clearly a more careful analysis of this is necessary before a true design of an experiment can be attempted, but it is believed that the agreement between calculation and experiment in the case of the ATHENA experiment is strong evidence for the principal validity of the SRIM2000 calculations. It is likely that the discrepancies observed here are due to the enormous thickness of the degrading foil, resulting in many more steps in the program and increasing the probability of error accumulation. Therefore any experiment in this regime needs to do careful experimental studies to fine-tune the design.

Once the optimum degrader thickness was established, a few runs with larger particle numbers were performed to obtain a value for the number of low-energy particles exiting from the degrader, as well as to study the radial straggling of the beam for the two cases. Figure 5 summarizes the results obtained for the 1 GeV/ c case. Figure 5a shows the transmission of particles through the degrader, which gives the optimum thickness as 10.88 cm. Figure 5b displays a histogram of the kinetic energy of the transmitted particles. The mean energy is around 28 MeV, with the highest energy observed to be near 70 MeV and only a small fraction of the 10,000 entries in this particular calculation registering below 1 MeV. Figure 5c gives the radial profile of the exiting beam (assuming a zero diameter incoming beam with no divergence) as 0.65 ± 0.35 cm. Including the correction for nuclear absorption, we find approximately 6×10^{-5} of the incident particles emerging from the degrader with an energy below 100 keV.

Increasing the momentum of the incident beam to 2 GeV/ c has a significant effect on these results. Firstly, we find that the thickness of the needed degrader is around 70.7 cm. Due to the radial straggling the beam spot at the exit of the degrader grows by a factor of 5 to 3.1 ± 1.6 cm. But the biggest effect is on the number of particles at low energy. In figure 6 the cumulative percentage of particles below a given energy threshold is plotted. The mean energy for the 2 GeV/ c case is 56 MeV, significantly higher than that for 1 GeV/ c . From a fit of the data to the range below 5 MeV we now obtain the fraction of transmitted particles below 100 keV according to SRIM2000 to be 4×10^{-5} compared to the value of 2.3×10^{-4} for 1 GeV/ c . Including the losses due to nuclear absorption, the efficiency is further reduced by four orders of magnitude to the final value of 8×10^{-9} , four orders of magnitude lower than in the case of 1 GeV/ c . Clearly, the statistics of these studies are not sufficient to give a final answer on the exact efficiency for a specific setup, but the trends are very clear. Even if one argues that the exact shape of the cumulative percentage at very low energy is not known, the most optimistic estimate would be a linear increase from 0 to 100%. In this case the raw efficiencies for both 1 GeV/ c and 2 GeV/ c obtained from SRIM would increase to 0.13% and 0.07% respectively, but adding the nuclear absorption corrections still renders the most optimistic numbers as 3.5×10^{-4} and 1.4×10^{-7} for the two momenta respectively.

Assuming the antiprotons in the Main Injector at Fermilab can be slowed down to a momentum of 1 GeV/ c just prior to ejection, the results discussed in the previous paragraph would present a possibility of capturing 2×10^8 antiprotons in a 100 keV deep trap, if the entire inventory is dumped in one shot. For the more realistic scenario of ejecting individual

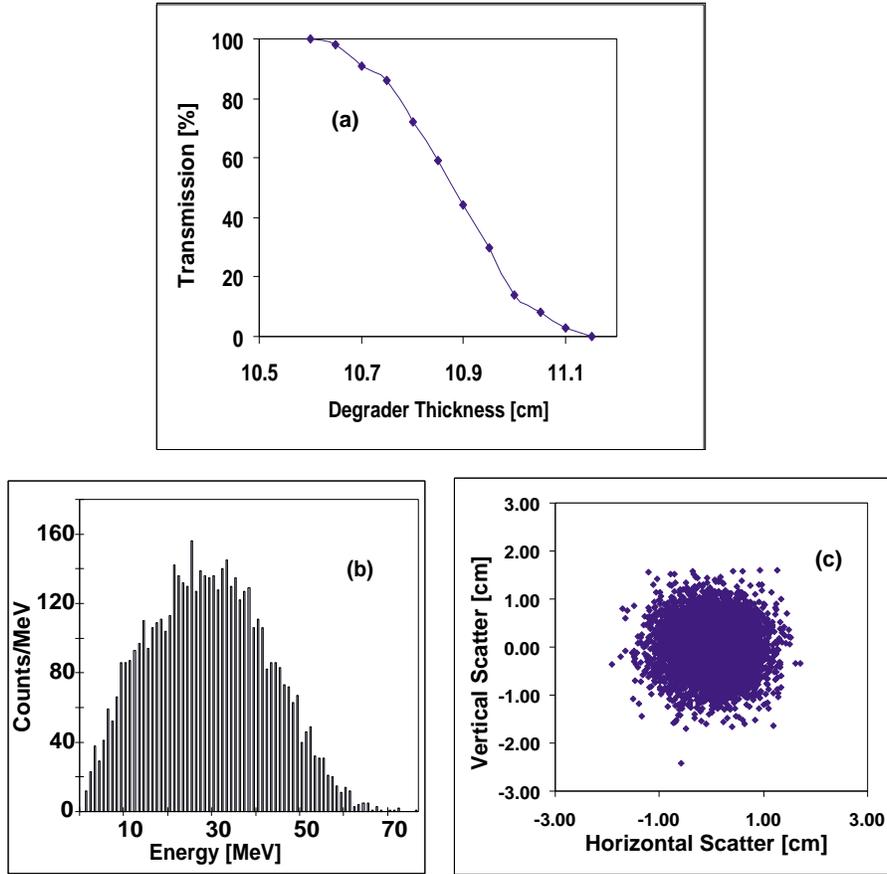


Figure 5: (a) Transmission of 1 GeV/ c antiprotons through osmium, (b) energy distribution of transmitted particles, and (c) spot size of beam emerging from degrader.

pulses of 2×10^{10} particles from the ring, the yield would be 2×10^6 , similar to the AD results, but still at the expense of constructing a Penning trap for significantly higher voltages and accordingly of a larger size. Using electron cooling to allow stacking higher quantities of antiprotons into the trap, each stack of antiprotons could be cooled to the bottom of the well in a time compatible with the few-minutes repetition rate for extraction from Fermilab. This method was originally developed at LEAR by both PS196 and PS200 [44] and has now been successfully implemented at the AD by ATHENA and ATRAP. These numbers are certainly sufficient for initial feasibility studies and demonstration experiments for many proposed applications and could well serve a wide community of physicists interested in fundamental physics.

Still, the question comes naturally to look for options to increase the capture efficiency through a better design of the degrading system. It has been proposed [45] that the straggling in the material can be compensated by adjusting the remaining thickness of the material depending on the previous history of the energy loss of the individual particles. A schematic of a possible implementation of this idea is shown in figure 7. Antiprotons are degraded to a

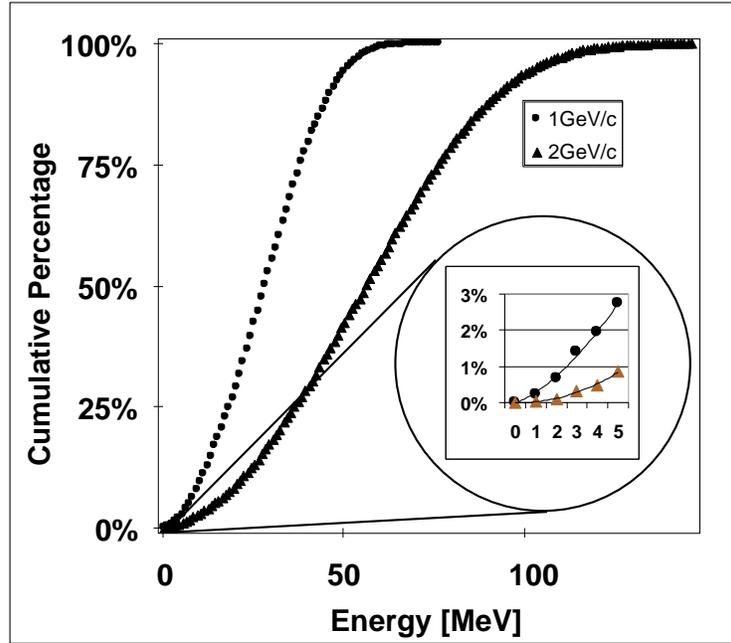


Figure 6: Cumulative percentage of particles per energy bin transmitted through the degrader for optimum thicknesses in both the cases of 1 GeV/c and 2 GeV/c. The inset shows the strong difference in efficiency at the lowest energy, which is of highest interest for the trapping of particles.

convenient intermediate energy, then energy-analyzed using a magnetic spectrometer, and, depending on the individual energy, guided to a specific thickness of degrading material. The antiprotons from the second degrader are then collected onto a small spot by magnetic focusing and allowed to impinge onto a final degrader to range out the particles. Such systems have been used for ion accelerators [46] to enhance the brightness of beams by about an order of magnitude, and similar results could be expected here.

To give an exact value for the brightness enhancement and to optimize the intermediate energies desired and the appropriate degrader thicknesses to be used, a full model calculation using GEANT must be performed. For practical reasons one would like to keep the bending radius of the spectrometer below one meter and use electromagnets or permanent magnets rather than superconductive systems. This sets the scale for the initial degrading step to reach an energy of approximately 100 MeV. An approximate estimate of the gain in brightness can be achieved using simple SRIM calculations of the individual steps. Degrading a beam from 1 GeV/c using 10 cm of osmium results in an intermediate energy of 95 MeV and introduces a straggle in the output energy of ± 10 MeV. In a 10 kGauss magnetic field the mean bending radius of the beam would be 1.4 meter and the beam spot would be spread laterally according to energy over a width of about 15 cm. Placing a wedge degrader which presents the low-energy side of the beam with 5 mm and the high-energy end with 7.5 mm of osmium will result in an average output energy across the entire wedge of 10.0 ± 3 MeV. This energy spread must be compared to the result of degrading the beam from 1

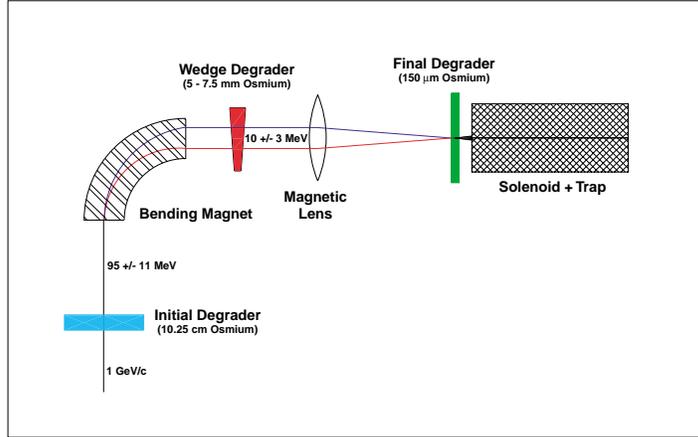


Figure 7: Schematic lay-out of magnetic spectrometer to enhance the brightness of the degrading set-up.

GeV/ c directly to the lowest kinetic energy achievable where no absorption in the degrader is observed yet, which is found to be 50 ± 15 MeV (using a single degrader of 10.7 cm of osmium). From these results one can expect an enhancement of at least a factor of five, or possibly more, considering the additional benefit of being able to maintain a small spot size throughout the degrading process using magnetic focusing between the different degrader sections.

4 Conclusion

In this report I show that under realistic operating conditions 10^7 or more antiprotons can be captured in a moderate-sized Penning trap from a single shot from the Fermilab Main Injector ring. The repetition rate of the individual capture events is well adapted to the time constants for electron cooling in Penning traps, which will allow stacking of several pulses into the trap, with the number of stacked pulses limited mainly by the vacuum achieved in the Penning trap and the resulting antiproton lifetime. Higher numbers of antiprotons (10^9 particles) could be achieved for specific requirements utilizing the entire Accumulator inventory of 2×10^{12} antiprotons in a single extraction. In order to achieve these numbers in a realistic experiment it is crucial to perform a careful design study of the degrading and beam guiding and focusing system. I have shown that the software for these tasks exists, and the performance of these codes has been quantified through model calculations and test experiments at CERN. Systematic discrepancies between different codes persist and a detailed analysis of these effects is necessary before a final assessment of the possible yields can be established.

Significant numbers of antiprotons can be captured at Fermilab with minimal modifica-

tions to the infrastructure or the operation of the facility and could be used for a number of fundamental experiments which cannot be served by the world's only existing low-energy antiproton facility, the CERN AD. Amongst these experiments those requiring continuous beams of antiprotons (or antihydrogen), such as the measurement of the gravitational acceleration of antimatter using matter interferometry [36] and the study of the hyperfine splitting of the ground state in antihydrogen [35], are in my opinion the most exciting ones, but many other programs, from a precision measurement of the magnetic moment of the antiproton [16] to atomic and nuclear collision studies using ultralow-energy antiprotons as projectiles [47, 48], would be feasible. In addition, the intensities of antiprotons achievable at Fermilab with these simple techniques suffice for feasibility studies and demonstration experiments for a variety of proposed applications of antiprotons in medical and space applications [49, 50]. A large and diverse user community exists and would be excited to hear about specific possibilities for antiproton physics at Fermilab. At this time the CERN AD is the only operating low-energy antiproton source in the world, and only serves a very limited community. Even a facility based on direct degrading at Fermilab could easily outperform the AD and serve a much broader community for many years until a new dedicated, multipurpose, low-energy antiproton facility would be build in either Europe [51] or Japan [52].

5 Acknowledgements

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