Chapter 4

Cryogenic Antiprotons

The antiproton is one of the few stable particles suited for long term storage and study in an ion trap. LEAR provides antiprotons which still have energies many orders of magnitude higher than the meV energies associated with confined electrons or protons in a trap cooled with liquid helium. To emphasize the new scale of our experiment, we recall that a supply of electrons and protons is obtainable using only a tiny field emission point (FEP) as an electron source. Our source for antiprotons, much of the CERN complex, covers more than 10^5 m^2. In this chapter, we describe our technique for trapping and cooling antiprotons for study at energies in thermal equilibrium at 4 K [37,44,45,28].

4.1 Antiprotons provided by CERN

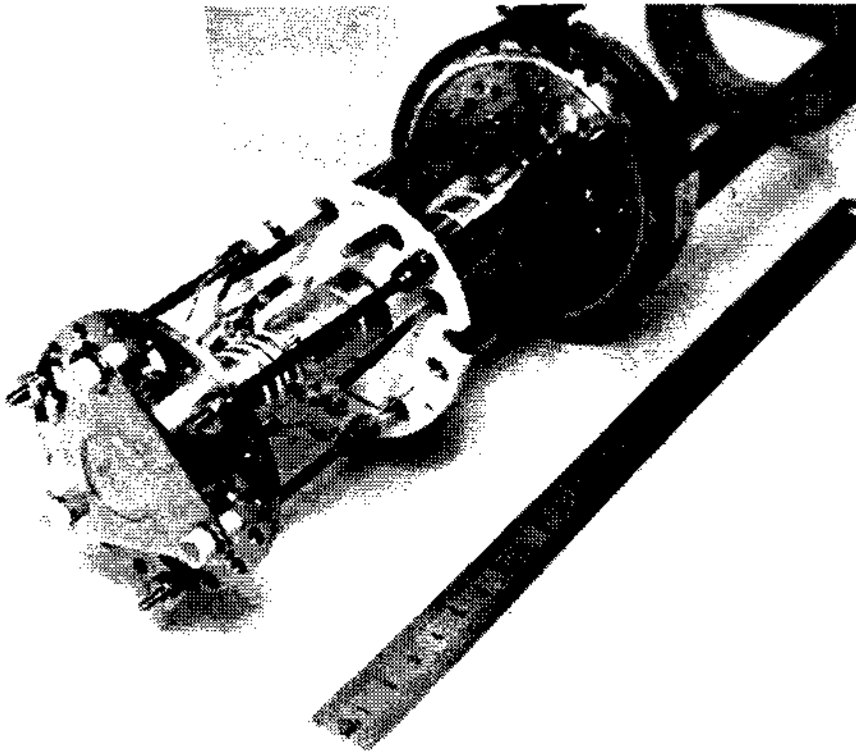
Antiprotons are created at CERN near Geneva, Switzerland. Four to six bunches of protons accelerate to 26 GeV/c in the Proton-Synchrotron (PS) machine every 2.4 seconds and collide with a fixed Iridium target. Antiprotons are produced by pair creation and are collected into the Antiproton Accumulator Ring (AA) with a momenta of 3.5 Gev/c. The AA and the Antiproton Collector (ACOL) collect, cool and store antiprotons at high energy for various experiments. The largest consumer of antiprotons at CERN is the Super-Proton-Synchrotron(SPS), for collision experiments with protons at energies up to 310 Gev.

For lower energy experiments, antiprotons are sent to the PS, decelerated to around 600 MeV and transferred to LEAR. In LEAR their momenta can be further increased (as high as 2 GeV/c) or decreased while keeping them cold using primarily stochastic cooling techniques. Presently, the lowest available momenta which LEAR generally provides is 105 MeV/c though recently 60 MeV/c antiprotons have been provided with substantially reduced beam quality. While these are low energies by CERN standards, it is still nearly 10 orders of magnitude higher than the cryogenic temperatures at which protons and electrons are studied in the trap (see Fig. 4.2).

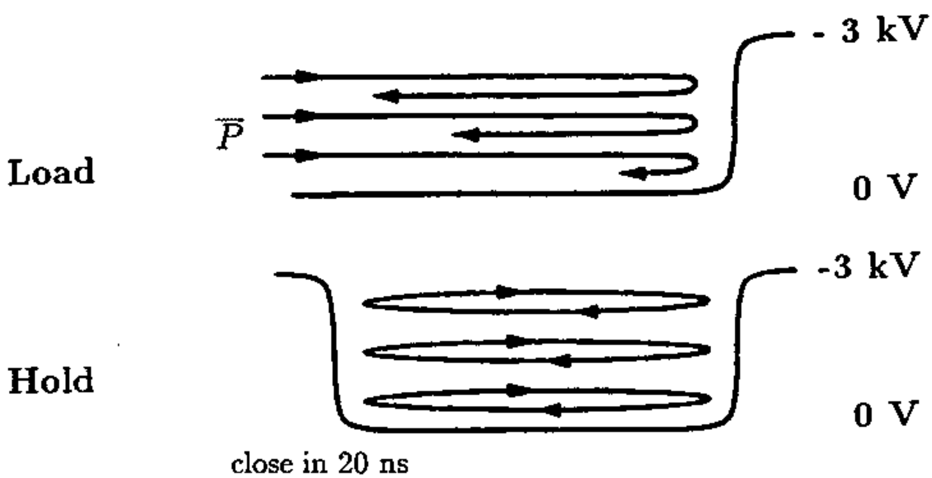
LEAR typically slows about 10^9 antiprotons to 5.9 MeV per fill cycle. For most experiments, LEAR operates in a 'slow extraction' mode, delivering antiprotons slowly and continuously over 1-3 hours. To obtain much higher intensities for loading antiprotons in our trap, the LEAR staff developed a 'fast extraction' mode of operation where they bunch the beam in their machine and provide a 200 ns pulse containing up to 3×10^{-8} antiprotons. In 1986, after first demonstrating the external loading of 1 keV protons [38], we demonstrated the first loading of antiprotons into a Penning trap using 200 Mev/c antiprotons from LEAR [37]. At the present, we receive the pulse of antiprotons with a momentum of 105 MeV/c (kinetic energy 5.9 MeV).

4.2 Energy Reduction and Confinement in a Penning Trap

To load the trap, we first reduce the antiproton energy by passing the beam through the degrader with the thickness carefully chosen to range out the antiprotons. The straggling width of the antiprotons that survive is about 1 MeV. Of the antiprotons which emerge from the degrader, most of them still have kinetic energies much too high for confinement in a Penning trap. Since easily obtainable voltages across the small dimensions of our trap are no more than a few kiloVolts, only the lowest energy antiprotons can be captured. Many of the slow antiprotons emerge from the degrader at large angles from the direction of the incident beam due to multiple scattering. Because the degrader already resides in a highly uniform field, most of the the transverse energy goes into the cyclotron orbit about



(a)



(b)

Figure 4.1: (a) The extended trap showing the gold plated aluminum degrader used to reduce the incoming antiproton energy to below 3 kV (scale in cm). (b) Schematic representation of the loading process and the potentials along the axis of the trap.

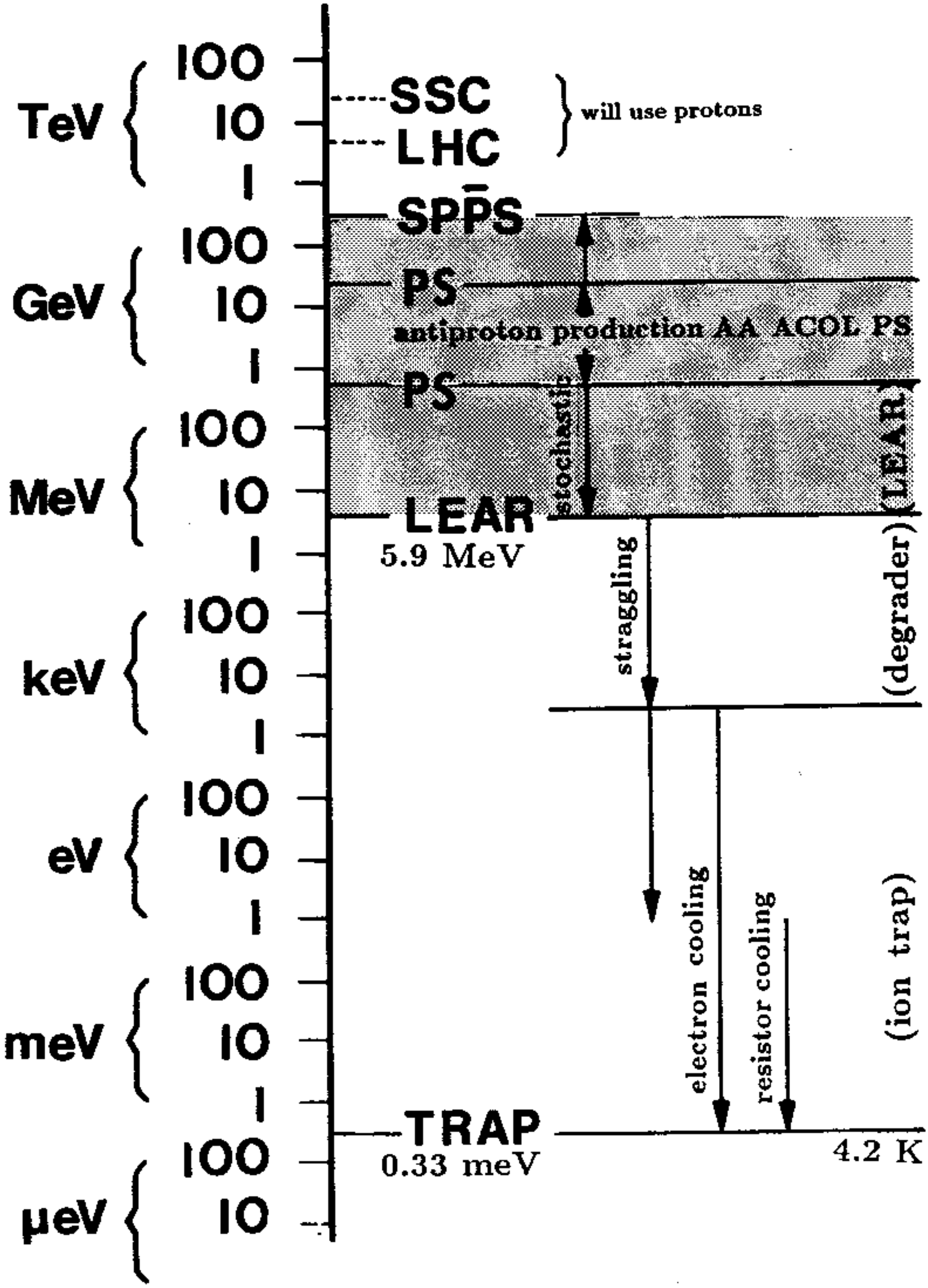


Figure 4.2: Antiproton energy scale summarizing our techniques to reduce the antiproton energy by more than 10 orders of magnitude.

a magnetic field line. Antiprotons with axial energies less than 3 keV travel slow enough to be captured in the trap shown in Figs. 3.4 and 4.1.

During the intense antiproton pulse, the degrader must be biased at more than +3 Volts to prevent low energy secondary electrons generated at the degrader from traveling into the trap (1.5 eV electrons travel with a similar velocity as 3 keV antiprotons). We typically bias the degrader with +100 V). The other trap electrodes are held at ground except the farthest electrode (the exit endcap) which is at -3 kV. With this arrangement, antiprotons emerging from the degrader with less than 3 keV of energy travel along the trap axis and turn around. Before the low energy antiprotons can escape through the entrance, the potential on the entrance endcap is suddenly lowered to -3 kV, confining the antiprotons along the trap axis completing the trap. The potential is switched in about 20 ns using a krytron switching circuit [27].

In the 1986 loading demonstration, the entrance electrode was a cylindrical ring around a beryllium degrader [37]. In the most recent version of the experiment, the degrader, seen in Fig. 4.1, is a 117 μm thick aluminum disk plated with a thin layer of gold (to prevent aluminum oxide buildup that might allow the degrader to charge in an uncontrolled fashion). The degrader, also used as the lower high voltage endcap, and upper high voltage endcaps are rigidly mounted on alumina insulators. The MACOR insulating spacers used in other regions of the trap were found to not be sufficient for holding potentials much above 1 kV.

In practice, the degrading matter consists of other materials such as titanium vacuum windows and aluminized mylar thermal shields. Fine tuning of the degrader thickness is accomplished using two gas degraders (Fig. 3.7). One degrader cell contains a mixture of helium and SF_6. The cell is kept at 1 atmosphere so that the pressure on the 10 μm thick titanium vacuum window is always kept constant. The relative ratio of the two gases allows a means of varying the effective density, and thus provide slight variations in the total degrader thickness. A second gas cell, also at one atmosphere, provides the possibility to make a larger discrete change by using either SF_6 or nitrogen gas. As an interesting sidenote, the total thickness of the degrading material to range out antiprotons and protons of equal incident energy of 5.9 MeV was measured to be different by about 5%, due to the Barkas effect [44].

Finally, steering profile and intensity information about the incident antiproton pulse from LEAR is obtained by a parallel plate avalanche counter (PPAC) [66]. This device sits between the degrading gas cells, measuring the incoming antiproton beam profile with a resolution of 2mm. Two orthogonal detectors indicate the X and Y steering. The detector operates with 70 Torr of isobutane (C_4H_{10}) and is made of non-magnetic and low density materials. The detector anodes are made by etching aluminized mylar and the thin windows are supported on a 90% transmission molybdenum grid. The total energy loss from the 5.9 MeV incident beam due to the PPAC's is 220 keV. Even though the detector resides in a field of nearly 1 Tesla, its efficiency is still better than 50%.

Using the technique described in this section we have successfully loaded more than 130 000 antiprotons in the long cylindrical trap with energies ranging between 0 and 3 keV from a single pulse of antiprotons from LEAR. Using the number of antiprotons to leave LEAR, we capture with an efficiency of 4×10^4. The real efficiency is higher (since not all of the antiprotons leaving LEAR reach our experiment) and could be increased by applying a larger trapping potential to a longer trap.

4.2.1 Measuring the Antiproton Energy

We analyze the axial energy distribution of the confined antiprotons by linearly reducing the exit endcap from -3 keV through 0 volts. Those antiprotons with an axial energy exceeding the endcap potential leak out of the trap. They annihilate upon striking the vacuum enclosure above, producing on average 3 pions for each annihilation, which are detected in six plastic scintillators that surround approximately $0.5(4\pi)$ steradians of the trap in the superconducting magnet (pion coincidences in two or more scintillators occur for 36% of the detected annihilations). Annihilations are detected with an efficiency measured to be $46.4 \pm 2.4\%$. This provides an absolute determination of the number of confined antiprotons.

The voltage ramp is linear in time, so the annihilation spectrum recorded in a

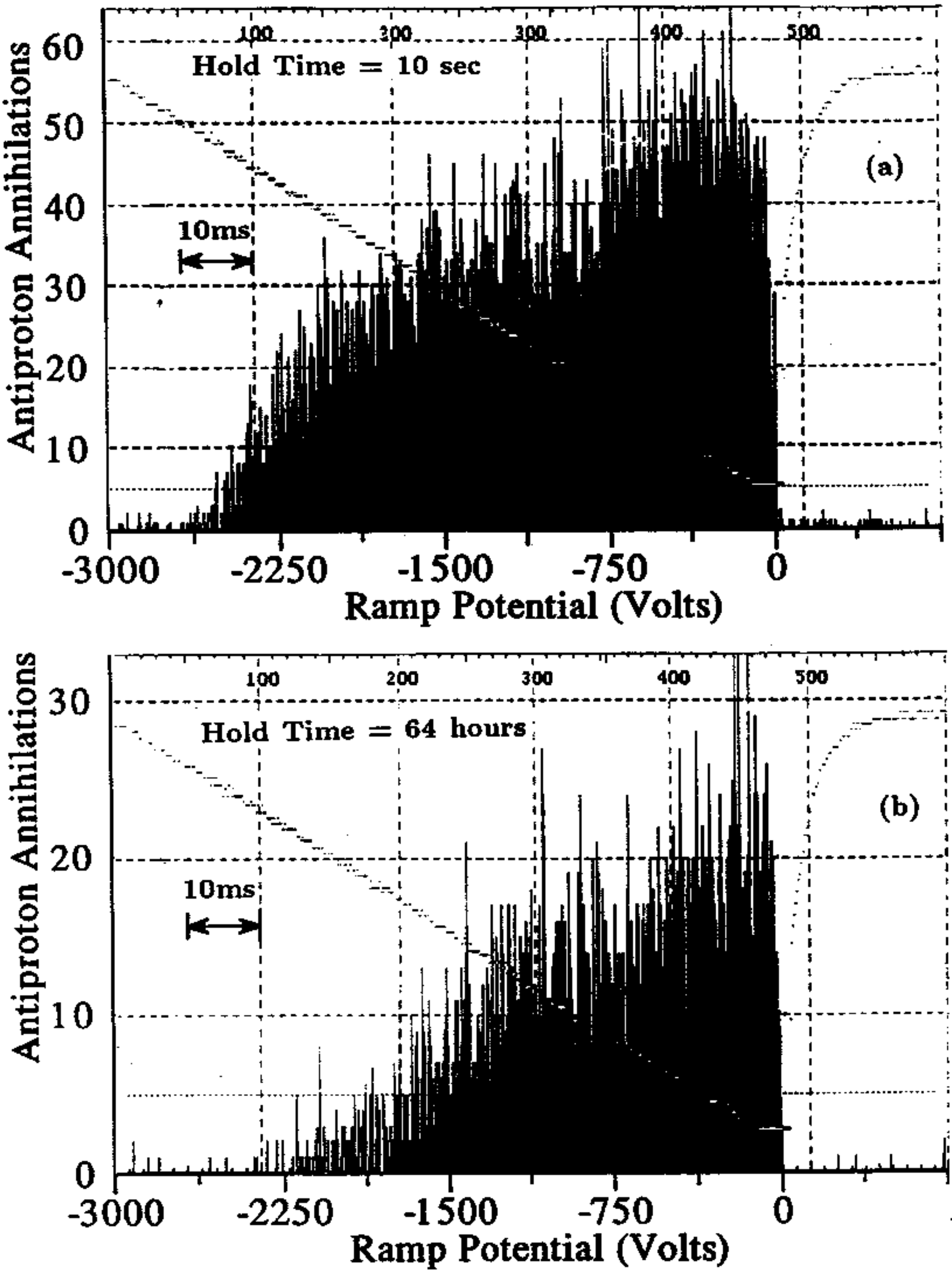


Figure 4.3: Energy spectrum for antiprotons after capture from LEAR into the long trap (a) after a 10 second holdtime and (b) after a 64 hour holdtime. The high voltage ramp as a function of time is superimposed for clarity.

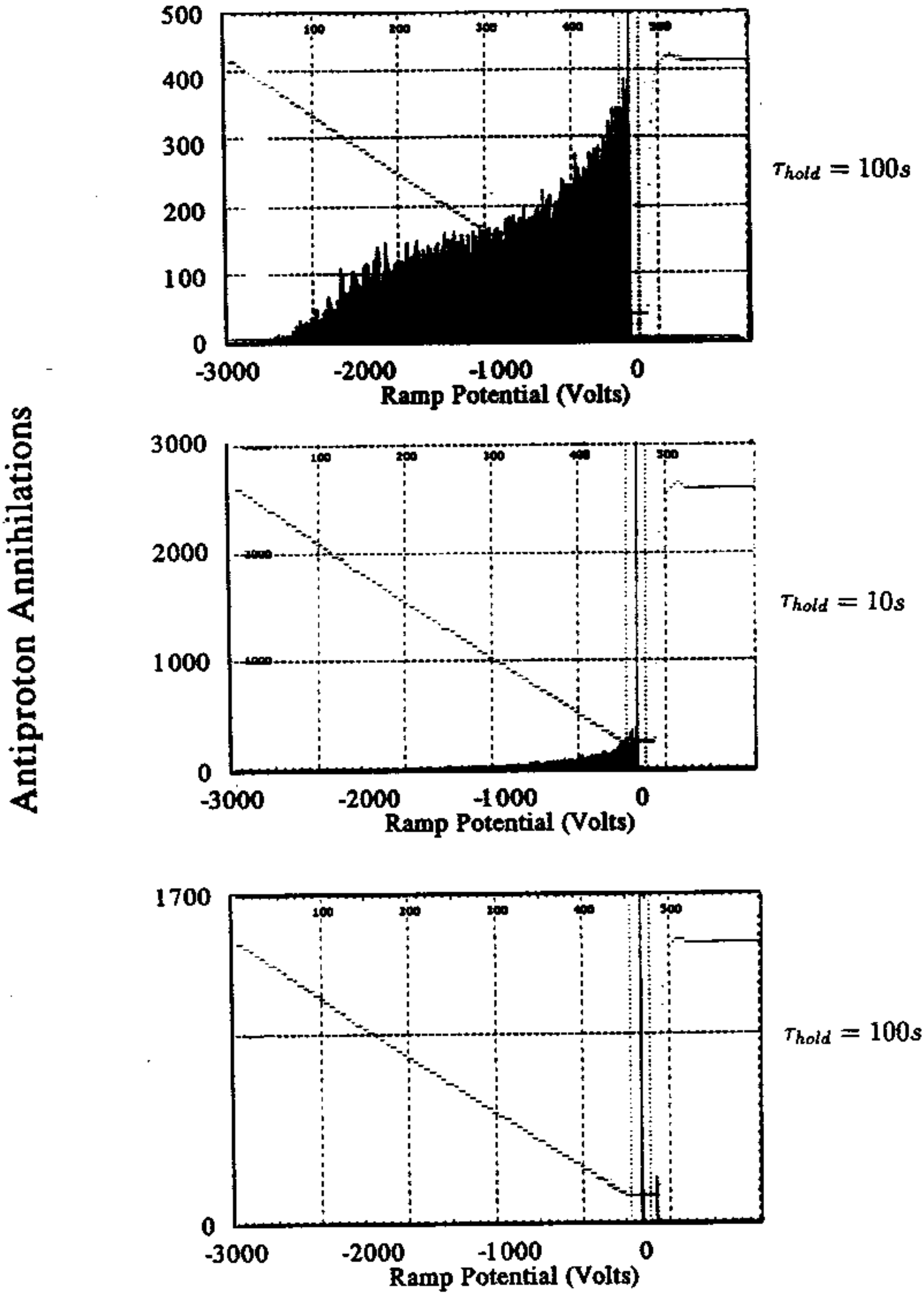


Figure 4.4: Electron cooling resulting from secondary electrons emitted from the degrader (a) in the long trap, and (b,c) in one-half of the long trap.

multiscaler during the ramp duration (typically 100 ms) is for our purposes here a direct measure of the antiproton axial energy spectrum. The energy distribution between 0 and 3 keV (Fig. 4.3) should be nearly uniform since it represents a narrow energy slice of the straggling spectrum emerging from the degrader (HWHM $\approx$ 100 keV). The lack of antiprotons above 2.5 keV results from the finite round trip length of the trap (ranging between 28 and 34 cm in different versions). The fall off of energies near the cutoff is a consequence of the incoming pulse having a duration near 200 nS.

In Fig. 4.3 we display energy spectra corresponding to two loads which originate from essentially identically steered shots and had nearly the same load intensity as seen in the PPAC detectors. The upper spectra is a very typical load of about 25000 antiprotons held in the long trap for 100 seconds. The lower spectra is a similar load, but confined in the trap for 64 hours. There appears to be some particle loss, which may be due to the stability of such a long trap for low energy particles [26]. The lack of damping in the energy spectra demonstrates the need for an efficient cooling mechanism to reduce the antiproton kinetic energy [61,84].

For sufficiently large shot intensities from LEAR, if the degrader is not biased with a positive potential, secondary electrons are emitted from the degrader. Electrons with an axial energy less than approximately 1.5 eV are also confined and will quickly synchrotron radiate to the 4 K trap environment and can cool the antiprotons. Figure 4.4 shows partial cooling of the antiproton spectrum. Since cold particles are not stable in the long trap and the densities are low, cooling is observed for only the most intense shots received from LEAR. When the trap length is shortened by a factor of 2 (Figs. 4.4(b) and (c)) the trap is more stable and the cooling is much more effective.

4.2.2 Electron Cooling into the Harmonic Well

Unlike the more massive antiprotons, electrons synchrotron radiate into thermal equilibrium with the environment with time constants on the order of 0.1 seconds. We control the cooling process by loading electrons into the harmonic well and then capture antiprotons in the long trap. The antiprotons oscillate the

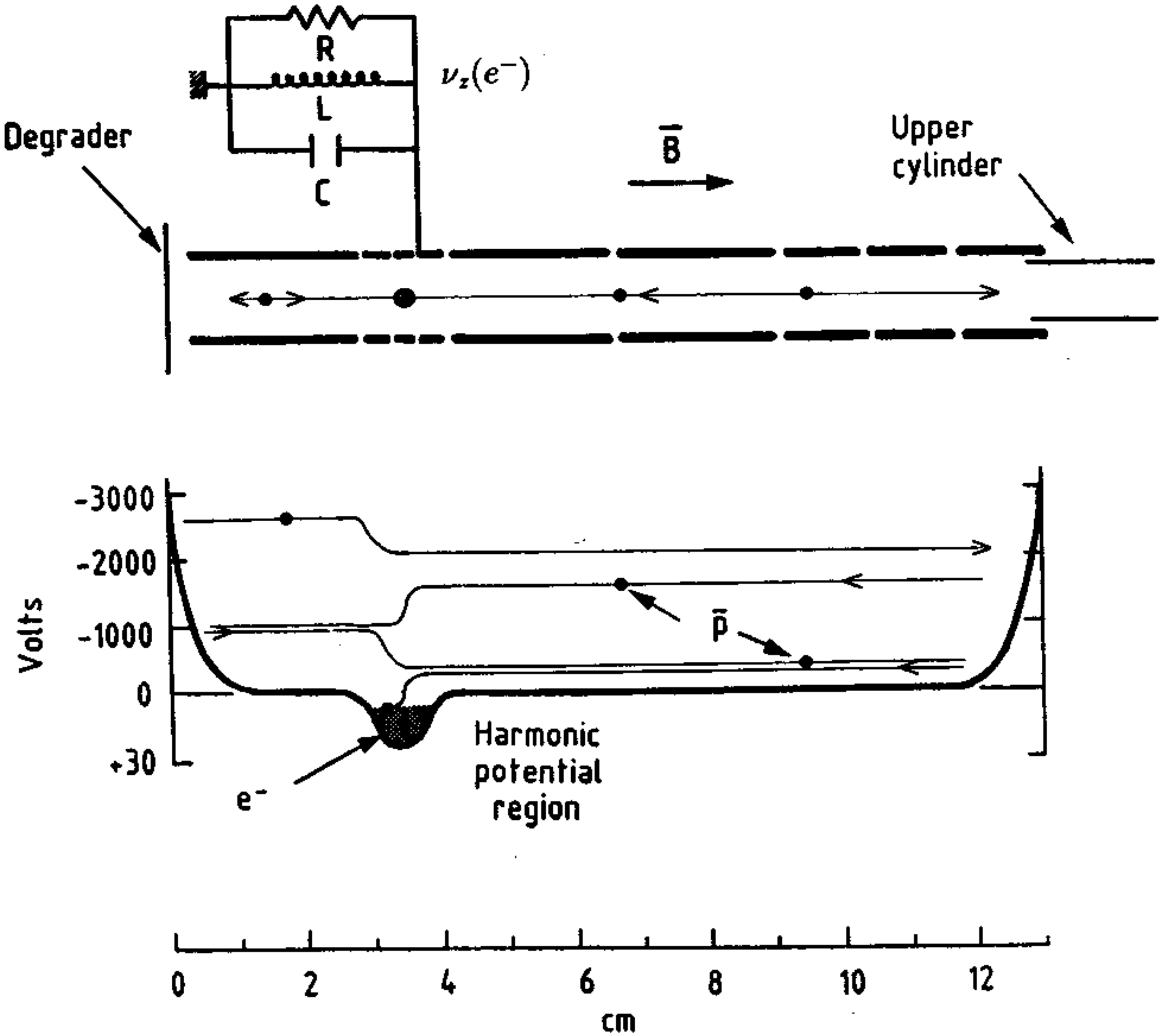


Figure 4.5: Schematic representation of the electron cooling process. The total cooling process occurs in less than 10 seconds.

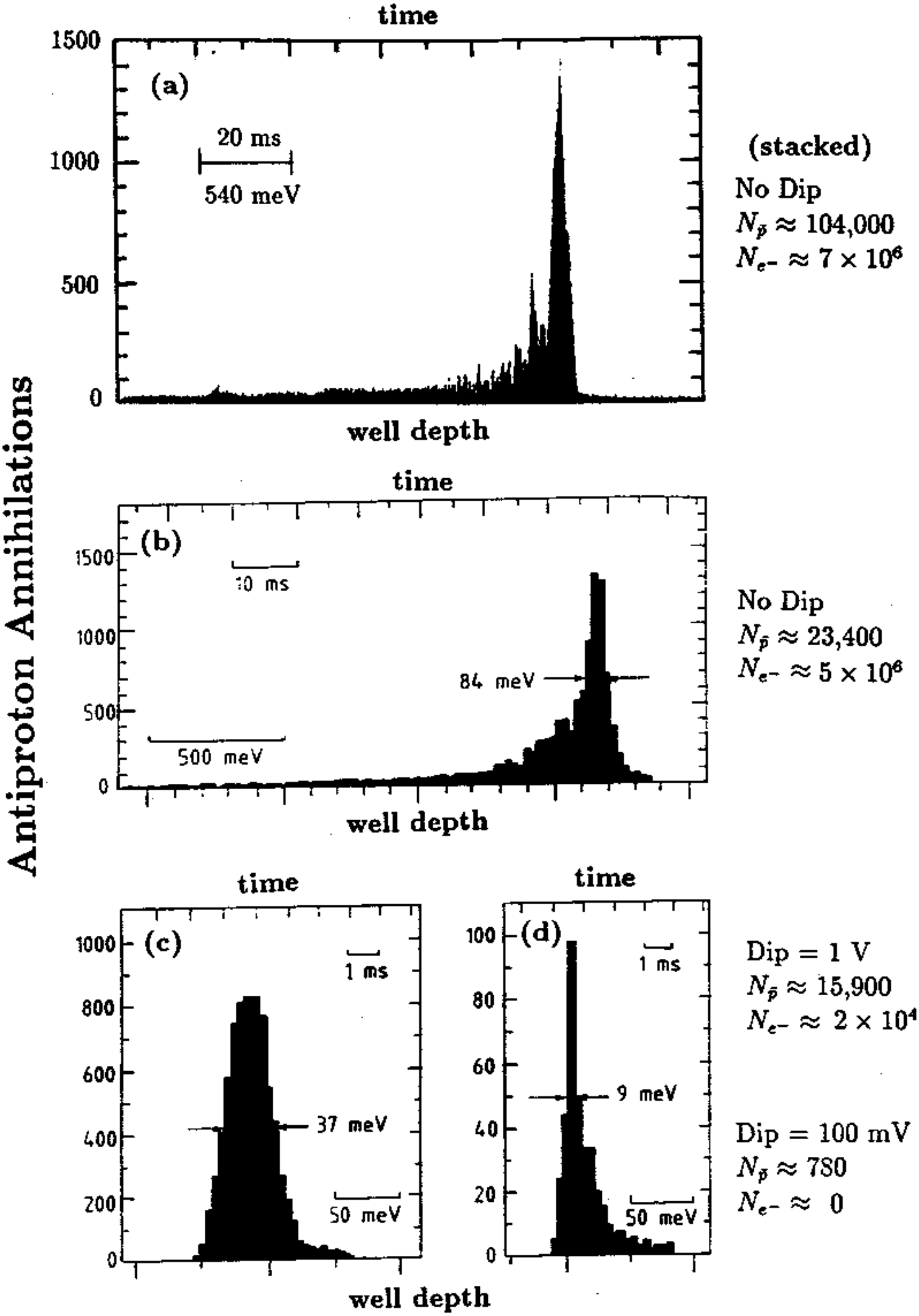


Figure 4.6: Antiprotons leaving the harmonic well as a function of well depth and particle number. (a) Annihilations from antiprotons stacked into the harmonic well. (b), (c), and (d) are obtained using only a single shot from LEAR.

length of the long well, losing energy via collisions with the cold electrons during each pass. The cold antiprotons eventually fall into the harmonic well with the cooling electrons at a rate depending upon the number(density) of antiprotons and electrons and the spatial overlap of the two particle species. The process is schematically shown in Fig. 4.5, and we typically use about 5×10^6 electrons to cool 2×10^4 antiprotons. With such ratios it typically takes less than 10 seconds to cool the 0-3 keV antiprotons to thermal equilibrium at 4 K, in good agreement with earlier cooling estimates [84].

After typically 100 seconds we lower the high voltage endcap and observe the remaining high energy spectrum. Usually a few remain, but the spectrum is shifted towards lower energies. Given enough time, if there exists sufficient spatial overlap between the antiprotons and the electrons, essentially all the antiprotons are cooled into the harmonic well. The size of the electron cloud is limited by space charge, and the location of the antiprotons depends upon how well the incoming antiproton beam is focussed and steered.

By linearly ramping the potential of the harmonic well and detecting annihilations in an analogous fashion to the previous section, we obtain energy spectra as seen in Fig. 4.6. The actual energy spectra observed are influenced by the ramping technique and the amount of charge in the trap. For larger numbers of cooling electrons and/or large numbers of antiprotons the spectra show the large axial heating of the antiprotons that results from the coulomb repulsion during the process of emptying the well (Figs. 4.6 (a) and (b)).

With electron cooling, the antiprotons residing in the harmonic well presumably are in thermal equilibrium at 4 K. Their energies are easily within a range where resistive cooling techniques are feasible.

Stacking

After an initial load and cool cycle, additional antiprotons can be loaded in the long trap between 0-3 keV and electron cooled into the harmonic well containing the cooling electron cloud and the cold antiprotons from the previous load. Within limitations, this process can be close to 100% efficient apparently until either the electron or antiproton cloud fills the well to its space charge limit. From time to time, especially with larger electron clouds, sudden loss of the electron and antiproton cloud is observed evidently resulting from instability mechanisms which at this time are not well characterized.

To be assured that the harmonic well is not filled to its space charge limit, we deepen the well depth by 5 V increments each time a new shot is stacked. Figure 4.6(a) shows the dump spectra from the harmonic well after about 10 shots from LEAR were sequentially loaded and stacked. The spectra, having some structure not entirely understood, shows the coulomb repulsion (heating) resulting from 104,000 antiprotons and nearly 10^7 electrons in the harmonic well.

4.2.3 Reducing the Number of Cooling Electrons

After the antiprotons are cold and localized in the harmonic well we turn our attention towards observing the antiproton particles by non-destructive means using the RF resistive detection techniques (Chapters 5, 6, and 7). At this point, after a single shot from LEAR, 25000 antiprotons typically reside in the well along with approximately 10^7 electrons. The large number of electrons perturb the oscillation frequencies of the antiprotons, making it essential to reduce the number of electrons for measurements of high accuracy.

The DC potential applied to the trap containing the mixed electron and antiproton cloud is typically around +32 Volts (to observe $\nu_z(e^-)$). We selectively reduce the number of electrons by exciting the electron axial frequency $\nu_z(e^-)$ with a drive strength of 180 mV_{rms} and simultaneously sideband cool the electrons with a drive near $\nu_z + \nu_m$ also at 180 mV_{rms}. After the drives have been on for about 15 seconds we suddenly reduce the well depth in 2.4 ms. (By observing scintillator counts during such a procedure we can monitor the loss of any antiprotons). The well is held at the low potential (typically +4 Volts, +1 Volts, +0.5 Volts etc.) for 600 ms and then restored to the original potential ($\approx$ 32 Volts). We then apply strong electron axial sideband cooling and observe the remaining number of electrons as described in Chapter 6.

This procedure ('drive and dip'), is very effective in preferentially reducing the electron number. We typically do not see annihilation pions during the first dip to +4 volts but do see a significant reduction in the number of cooling electrons (from $10^7 \rightarrow 10^5$, a 99% reduction). After the first dip we can easily detect the antiprotons by non-destructive means. In Chapter 8, we describe antiproton cyclotron measurements made with residual electrons remaining. In Chapter 9, we describe measurements made with essentially all the electrons removed by repeated application of the 'drive and dip' procedure.

4.3 Confinement Lifetime of 4.2 K Antiprotons

Antiproton collision and annihilation cross sections rapidly increase at lower energies placing stringent vacuum requirements in the trapping region. We obtain a low pressure by cooling the trap and its vacuum enclosure to 4 K. Shortly after we first successfully cooled antiprotons to 4 K we observed that the containment lifetime was much greater than 1 hour which is critical for performing mass comparisons at the highest precisions.

Recently, we had an opportunity to put a lower limit on our confinement lifetime. During January and February the CERN accelerators are shut down for maintenance and upgrading. On December 20 we loaded the trap, cooled the antiprotons to 4 K, and ejected most of the electrons using the drive and dip procedure. We then observed the antiproton cyclotron motion daily for nearly 2 months using non-destructive RF detection techniques (Fig. 4.7), and could observe no antiproton losses within the resolution of our system. After 58.7 days, on February 17 we opened the well and counted the annihilation pions. We measured $N_{\bar{p}} = 1850 \pm 40$ antiprotons.

To obtain a lifetime limit, we infer the original number of antiprotons loaded by comparing the integrated PPAC signal to the signal of the most efficient load we had. We then subtracted out the number of antiprotons lost during the drive and dip procedure. Imprecision in our knowledge of the number of antiprotons initially loaded limits the lifetime we can set to

$$\tau_{\bar{p}} > 8.9 \times 10^6 s \tag{4.1}$$

or a lower limit of 103. The 58.7 day hold time corresponds to the longest antiproton containment time at any energy. The Antiproton Accumulator (AA) has held a single load of antiprotons at 3.5 GeV/c for 11 days (only losing them due to a power failure) and were able to achieve a containment lifetime of 154 days or 1.3 $\times 10^7$ seconds, though because of the high energy, a rest frame lifetime can be set of $\tau_{\bar{p}} > 3.4 \times 10^6$ s [2].

The similar containment lifetimes, despite our much lower energy (13 orders of magnitude), is a reflection of the ultra high vacuum in our cryopumped vacuum

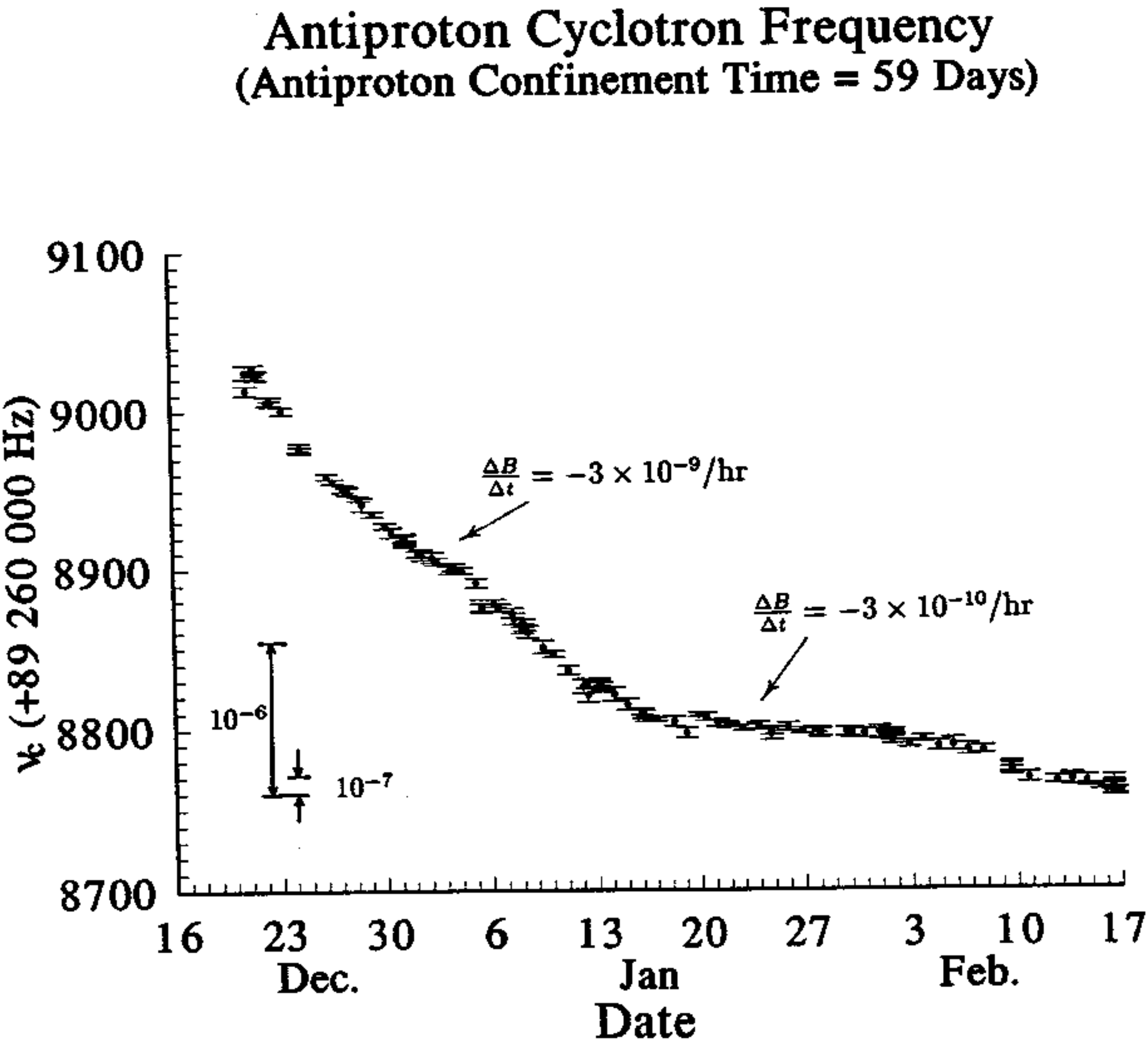


Figure 4.7: Antiproton cyclotron frequency measured on a cloud of 1850 antiprotons over a two month period using techniques described in Chapters 5 and 9.

enclosure. Based upon calculated annihilation cross sections [73,7], the containment time we observe requires a background density of less than 100 atoms/cm^3 [28]. For an ideal gas at 4.2 K this would correspond to a background gas pressure of

$$P < 5 \times 10^{-17}\ Torr. \tag{4.2}$$

The antiproton containment lifetime is normally very long in our Penning trap, though on one occasion the trap was contaminated with helium so that when attempting to load positive ions, only He^{+} and He^{++} could be identified. Presumably some weakly cryoadsorbed helium was also present on the degrader. Nevertheless, antiprotons could be loaded and electron cooled into the harmonic well. Non-destructive cyclotron measurements (Chapter 8 and 9) could also be performed on the confined antiprotons even though the helium contamination was present. After about 2 hours antiprotons could no longer be detected either non-destructively, or when dumping the trap. The containment time, as expected, was compromised by the helium.