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COOLING ANTIPROTONS IN AN ION TRAP

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The measurement of the inertial mass of the antiproton and proposed antihydrogen formation experiments require antiprotons stored in ion traps, cooled to very low (4 K) temperatures. Techniques to cool the trapped antiprotons from energies around 1 keV are discussed. Coupling to an external circuit produces cooling times of order 10^3 s, which may be reduced somewhat with negative feedback. Adiabatic reduction of the trapping potential produces significant cooling when the particle energies are substantially less than the well depth. Most promising is cooling via energy-transferring collisions to a cooled cloud of electrons simultaneously trapped with the antiprotons. Electron cooling times are of order 1 s, and strongly depend on electron number and density.

1. Introduction

The experiment [1] to measure the inertial mass of antiproton to high precision in a Penning trap requires that the trapped antiprotons be at very low (4 K) temperatures so that the amplitude of oscillations in the trap are small to reduce magnetic field inhomogeneity and potential anharmonicity effects. A recent proposal [2] for the formation of antihydrogen by combining antiprotons and positrons in an ion trap also required cold antiprotons due to recombination processes that depend strongly on the inverse of the temperature. Antiprotons at 21 MeV from LEAR (the Low Energy Antiproton Ring at CERN) have been slowed in a degrader foil and trapped in a Penning trap [3], with −3 kV applied to the endcaps. The trapped antiprotons were distributed in energy below 3 keV. Various techniques may be applied to reduce the energy of the trapped particles. These can be grouped into three catagories: resistive techniques in which the charged particle motion induces a current in an external resistor coupled to the trap, producing particle cooling through Ohmic losses in the resistor; adiabatic cooling where an adiabatic reduction of the trap well depth produces particle cooling; and collisional techniques that utilize collisions with other particles (electrons) to cool the antiprotons. These techniques all have different time constants associated with them, and have certain limitations which are discussed.

Before discussing cooling techniques, it is important to review particle motion in a Penning trap [4]. A single particle undergoes periodic motion with three characteristic frequencies. Cyclotron motion due to the magnetic field has the highest frequency (90 MHz for antiprotons in a 6 Tesla field). The particle undergoes simple harmonic motion in the axial direction due to the quadratic potential applied, with a characteristic frequency dependent on the square root of the potential, usually in the 1–5 MHz range. The third motion is termed magnetron motion, a slow drift due to the crossed electric and magnetic fields, with a frequency of 10–100 kHz. There is very little kinetic energy in the magnetron motion and cooling of this motion, while important, will not be discussed. When a particle is loaded into a trap its kinetic energy is divided between the axial and cyclotron motions, depending on the transverse momentum during loading. There is no coupling between the three motions for a single particle in an ideal Penning trap, so the energy in each motion can be considered separately. When a cloud of particles is trapped, collisions couple the cyclotron and axial motions, with a coupling time constant [5] of much less than a second for a cloud of $\geq 10^3$ particles. A cloud of N particles has an energy associated with the motion of the center of mass (c-m) (which is detected) and additional energy in the $N-1$ internal degrees of freedom of each type of oscillation: cyclotron, axial, and magnetron. A perfectly harmonic trap does not produce any coupling between the internal and c-m motion, but deviations from a pure quadratic potential and magnetic field inhomogeneity couples these motions. Cooling of high energy antiprotons requires cooling the axial and cyclotron c-m motions and the energy in the internal degrees of freedom.

2. Resistive cooling

Many high precision experiments on elementary particles stored in Penning ion traps detect particle motion through the measurement of the voltage drop across a resistor which is placed across the trap electrodes (fig. 1). The voltage is produced due to the current induced by the particle axial motion. This induced current produces Ohmic losses in the resistor which reduces the energy in the

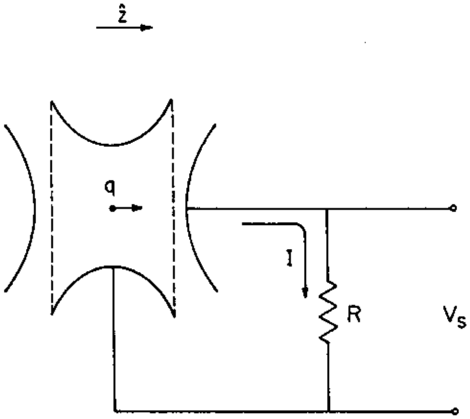

Fig. 1. Idealized schematic of the tuned circuit used for particle detection and resistive cooling.

particle motion until it is in thermal equilibrium with the resistor. The time constant for the coupling of a single particle to the resistor can be written as [6]:

$$\tau_R = \left(\frac{2z_0}{e\kappa} \right)^2 \frac{m}{R} \tag{1}$$

where the particle has charge e and mass m, z_0 is a characteristic dimension of the trap, κ is a constant of order unity dependent on the electrostatics of the trap [7], and R is the resistance of the resistor in which the induced current flows. In practice the resistor is replaced by a tuned circuit with an effective resistance of $R \approx 1 \times 10^5\ \Omega$ at the resonant frequency. The time constant for a typical trap with $z_0 = 1$ cm, and for the proton mass, is $\tau_R = 270$ s. This time constant is very long for practical experiments, especially when one considers that this pure exponential decay of the particle energy requires $14\tau_R$ to cool from 1 keV to 5 K.

This is the time constant for a single particle. For a cloud of N particles the c-m motion cools much more rapidly with a time constant τ_R/N since each particle experiences the damping force generated by the others. For a cloud it is important to distinguish between cooling of the c-m motion and cooling the total energy including the $N-1$ internal degrees of freedom of the axial or cyclotron motions. The total energy, which is the relevant parameter for these experiments, decays much more slowly than the c-m energy. If we consider the most favorable case where the coupling between the internal motion and the c-m motion, τ_{ci}, is much less than τ_R/N, the temperature of the thermal reservoir consisting of the internal degrees of freedom is equilibrated with the c-m temperature. Although the temperatures are equal, the c-m energy is only $1/N$ of the total energy, since the internal degrees of freedom have $N-1$ times more heat capacity. The decay of the total energy is reduced by this factor which exactly cancels the increase in the rate of energy lost from the c-m motion. The net effect is that the cooling of the total energy of the cloud has at best the single particle time constant, τ_R. This is simply a statement that there is no coherent process available to allow N particles to dissipate their energy any faster than they can lose energy individually. If τ_{ci} is greater than τ_R, the limit to the rate of cooling is determined by how rapidly energy can be extracted from the internal degrees of freedom. In one coupling time, τ_{ci}, only $1/N$ of the energy can be extracted due to the differing heat capacities, leading to a time constant $N\tau_{ci}$ in the limit where τ_{ci} is much larger than τ_R. In no case can the cloud cool faster than a single particle. A cloud of antiprotons in a trap require more than 10^3 s to cool from a temperature of 1 keV to 5 K.

A large additional increase in this long cooling time can occur because the resistor is actually a tuned circuit with $Q \approx 500$. Full utilization of the resistive cooling requires the particle frequency to be within the bandwidth of the tuned circuit. When the particles are first loaded with high energies, they have very large amplitudes of oscillation, carrying them into regions of the trap that are not harmonic. This causes an energy dependent shift in their resonance frequency, possibly outside of the bandwidth of the tuned circuit. This substantially reduces R, increasing the cooling time. The obvious solution of a very large harmonic trap is not feasible because the time constant increases with a $(z_0)^2$ dependence. It may be possible to circumvent this problem by constructing a trap out of many small cylindrical segments. Each segment would be biased to provide a quadratic potential along the axis but the coupling could be increased because the segments could be much closer to the particles than the characteristic dimension of the potential. Great care must be taken to retain harmonicity in such a configuration, and the detection becomes quite complicated due to the many electrodes.

Although the discussion has focussed on cooling the axial oscillation, the cyclotron motion can be cooled analogously by splitting the ring electrode into two or more segments and using a tuned circuit at the cyclotron frequency. We will continue to use the axial motion for examples, with the understanding that the same results can be applied to the cyclotron motion.

3. Negative feedback and stochastic cooling

Negative feedback can be used to increase the single particle damping rate. The coupling to the external circuit is increased by using the amplitude and phase information about the particle motion to apply a negative feedback driving force to slow the particles. Figure 2 shows a continuous feedback method where the signal from the particle is amplified with gain G, and fed back onto the trap electrodes with a 180° phase shift. The time constant for energy decay of the particle is reduced to [8]

$$\tau_f = \frac{1}{1+G}\tau_R. \qquad (2)$$

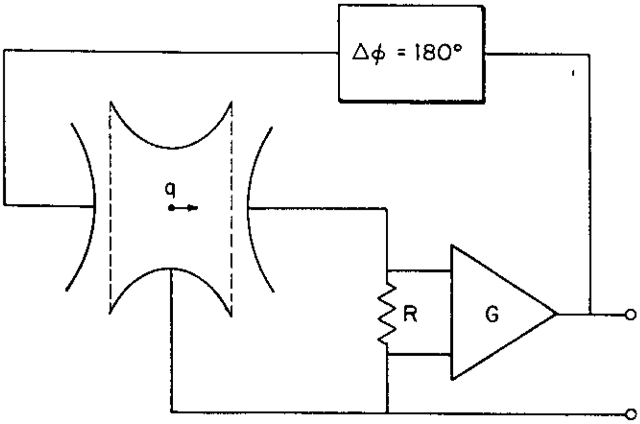

Fig. 2. Schematic of negative feedback enhanced cooling with feedback gain G, and a phase shift of 180°.

A gain of 10 could lower the time constant from 270 to 24 s. Unfortunately the amplifier also amplifies the thermal noise associated with the resistor so that instead of coming into thermal equilibrium with the temperature of the resistor, this feedback method produces a higher particle temperature,

$$T_\mathrm{f} = (1 + G) T_R \tag{3}$$

where T_R is the temperature of the resistor. The product of the cooling time and the lowest attainable temperature is independent of gain, since from eqs. (2) and (3)

$$\tau_\mathrm{f} T_\mathrm{f} = \tau_R T_R . \tag{4}$$

One could imagine a cooling sequence in which the gain is lowered as the particle energy decreases to obtain fast cooling at high energies, and low temperature limits when the particle is cool. In practice, direct feedthrough of the drive into the detector electronics and amplifier performance limit the maximum usable gain. For a cloud, a high gain can also move the system into the regime where the cooling is limited by the coupling of internal and c-m motions, and further increases in gain will not increase the total cooling rate.

The stochastic cooling technique recently applied to trapped particles [9] is a special case of negative feedback. This method minimizes direct feedthrough problems by separating the drive and detection in time. A short pulse is fed back with phase and amplitude adjusted to produce an impulse to cancel the center-of-mass momentum of the oscillating particles. After waiting a time determined by the coupling of internal to c-m motions, there will be energy in the c-m motion again. A stopping pulse can then be applied and this process repeated to eventually cool the particles to an equilibrium temperature related to the temperature of the detection electronics. The minimum time constant is $N\tau_{ci}$ since the coupling of energy out of the internal modes is the limiting process. It can be shown [9] that the same relationship between the equilibrium temperature and the cooling time constant exists as in eq. (4), with an effective gain dependent on the size of the slowing pulse. Stochastic cooling of trapped particles with a stopping pulse is essentially the application of negative feedback with a very high gain for short periods of time. It uses narrow band detection unlike the broadband methods used in stochastic cooling in storage rings.

These negative feedback methods can reduce the cooling time of particles in a trap, but are susceptible to the same bandwidth limitations as normal resistive cooling, and the rate at which energy can be transferred out of the internal degrees of freedom. An estimate of the largest cooling rate is obtained by setting the coupling time for the internal and c-m motions, τ_{ci}, equal to the bandwidth of the detection circuitry. This coupling, due to trap anharmonicity, is a measure of the spread in particle axial frequencies, and as mentioned previously, if the spread is too large the effective resistance of the tuned circuit decreases, leading to an increase in the cooling time. Moreover, the cooling time lengthens in proportion to the number of particles, making this method less useful for large clouds of trapped ions. The fastest cooling time (setting the coupling time equal to the bandwidth) for a cloud of 10^5 particles with an axial frequency of 1 MHz, and a detector with $Q = 100$, is 10 s. This is a lower limit that significantly overestimates the possible decrease in cooling time. The internal and c-m motions are coupled because particles of different energies oscillate at slightly different frequencies. As the ions cool, their amplitudes decrease and the spread in axial frequencies lessens, leading to a longer coupling time. A ten-fold decrease in particle energy produces a ten-fold increase in the cooling time constant. A trap that was built to be harmonic enough to keep 1 keV antiprotons within the detector bandwidth of the previous example only allows a cooling time constant of 1000 s when the 10^5 particles have cooled to 10 eV. It is apparent that feedback techniques become significantly less effective as the particles lose energy. It may be possible to counter this effect somewhat by increasing the anharmonicity of the trap as the particles cool.

Feedback techniques can reduce the cooling time, but present some technical challenges. These include a high gain feedback system, especially necessary in a large trap with a long single particle time constant. The feedback gain must decrease as the cooling proceeds to assure a low final temperature. In addition, the trap must have an increasing anharmonic term as particle energy is lost to maintain a reasonably short time constant determined by the internal to c-m motion coupling.

4. Adiabatic cooling

Adiabatic cooling is based on the principle that for adiabatic changes in the spring constant of an oscillator, the quantity E/ω remains constant, where E is the energy, and ω the frequency of oscillation. The definition of an adiabatic change is that the change in ω per period is much less than ω. This is easily satisfied for axial oscillations near 1 MHz. The axial oscillation frequency ω is proportional to $V^{1/2}$ where V is the potential applied to the trap. If V is reduced, ω is reduced, and as long as this reduction is adiabatic, E is also reduced. Since the reduction of E is dependent on the square root of V, the well depth drops faster than the particle energy, and there is a limit to the cooling where the energy of the particles is equal to the well depth. The energy limit E_{lim} is

$$E_{\text{lim}} = \left(\frac{E_{\text{i}}}{W_{\text{i}}}\right) E_{\text{i}} \tag{5}$$

where E_{i} is the initial energy and W_{i} is the initial well depth. It is apparent from this expression that adiabatic cooling is only applicable when the initial energy is less than the well depth. This is of course not the case when antiprotons are initially loaded into the trap, but this method might be useful in some later stage of cooling. One unfortunate consequence of adiabatic cooling is that the amplitude of the oscillations increase by an amount $(W_i/W_f)^{1/4}$. This is somewhat contrary to the goal of low energy antiprotons confined to a small region of space.

5. Electron cooling

A two component plasma in which the two species have different initial temperatures comes into thermal equilibrium via collisions with both species approaching the same temperature. This process has been used to increase phase space density in beams circulating in storage rings by passing a velocity matched electron beam through the circulating beam [10]. The circulating beam comes into thermal equilibrium with the temperature of the electron beam. This same concept can be applied in a Penning trap [11], and is in fact more closely the situation analyzed in plasma studies [12]. Consider a Penning trap simultaneously holding clouds of antiprotons at temperature T_p and electrons at temperature T_e and density n_e. Electron densities of 10^7 cm^{-3} are routinely achieved in Penning traps, and an electron density $\geq 10^{10}$ cm^{-3} has been demonstrated [13]. The temperature of the electrons can be maintained near 4 K by synchrotron radiation cooling or by coupling to a cooled circuit resonant at the electron axial frequency. The time constant for equilibration of the temperatures can be written as [12]:

$$\tau_c = \frac{3 m_p m_e c^3}{8(2\pi)^{1/2} n_e e^4 \ln \Lambda} \left(\frac{kT_p}{m_p c^2} + \frac{kT_e}{m_e c^2} \right)^{3/2} \tag{6}$$

where m_p and m_e are the masses of the antiproton and electron, and $\ln \Lambda$ is the Coulomb logarithm that arises from a cut-off in the integration over impact parameters due to Debye shielding of the Coulomb force. Λ is the ratio of Debye length to minimum impact parameter, and can be written as:

$$\Lambda = \frac{4 \times 10^3}{\sqrt{n_e}} \sqrt{T_e} \left(T_e + \frac{T_p}{1836} + \frac{\sqrt{T_p T_e}}{21} \right). \tag{7}$$

The Coulomb log has typical values of 10–20 during the cooling process. These expressions assume thermal distributions for both the electrons and antiprotons. The electron distribution should be very close to a Maxwell-Boltzmann distribution. The antiproton initial distribution is determined by the energy distribution of particles exiting the foil degrader and capture efficiencies. Collisions with the electron cloud should help evolve the distribution towards a thermal shape. In addition, the time constant is probably not extremely sensitive to the details of the distribution. This type of analysis has been quite successful predicting the

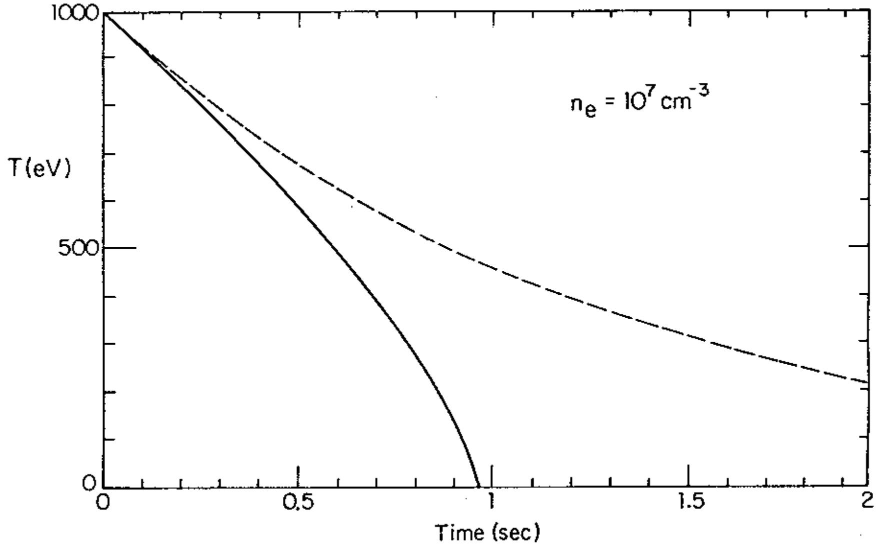

Fig. 3. The electron cooling process. The solid curve is calculated cooling, demonstrating the non-exponential behavior of the process. The dashed curve is a pure exponential decay with the 1 keV time constant.

behavior of electron cooling in storage rings, where the energy distribution is not necessarily thermal.

The important dependence to note in τ_c is the last term which is essentially the relative velocity cubed. The cooling process accelerates as the antiprotons cool. This leads to a non-exponential decay of the antiproton energy which is much more rapid than a pure exponential. Figure 3 shows the energy decay for antiprotons with initial temperature of 1 keV. The solid line is calculated with the time constant expression shown above, while the dashed line is a pure exponential decay, using the 1 keV time constant. Note that the v_{rel}^3 dependence of τ_c significantly decreases the time to reach low temperature. This was calculated with the electron temperature fixed at 4.2 K. In practice, there are a finite number of electrons in the trap, and the addition of a number of very hot antiprotons may raise the electron temperature. The electron cloud is limited by its coupling constants in how rapidly it can dissipate the energy from the antiprotons. This can be modeled with the following rate equations:

$$\frac{\mathrm{d}}{\mathrm{d}t} T_{\mathrm{p}} = -\frac{1}{\tau_{\mathrm{c}}}\left(T_{\mathrm{p}} - T_{\mathrm{e}}\right) \tag{8}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t} T_{\mathrm{e}} = \frac{N_{\mathrm{p}}}{N_{\mathrm{e}}} \frac{1}{\tau_{\mathrm{c}}}\left(T_{\mathrm{p}} - T_{\mathrm{e}}\right) - \frac{1}{\tau_{\mathrm{e}}}\left(T_{\mathrm{e}} - 4.2\right) \tag{9}$$

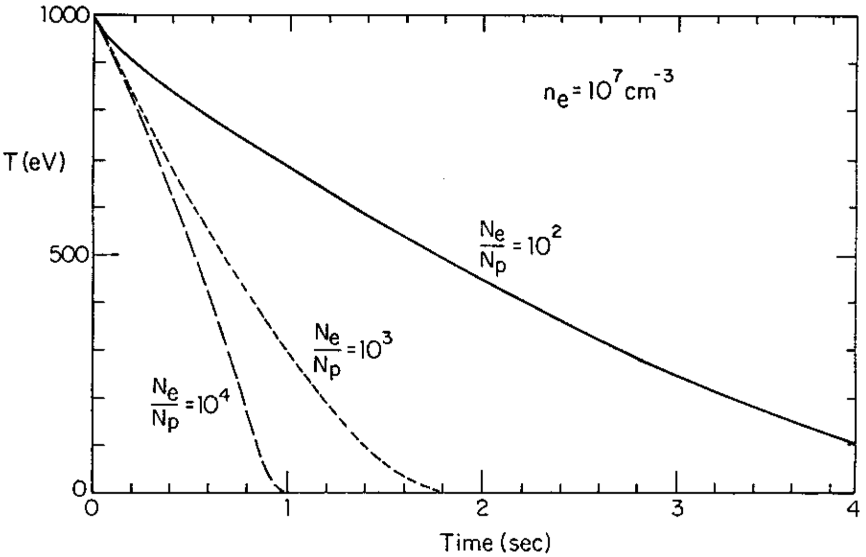

Fig. 4. The dependence of the electron cooling process on number of electrons. The three curves are calculated for different ratios of electrons to protons, as labeled.

where N_p and N_e are the total number of antiprotons and electrons sharing the same volume, and τ_e is the coupling time (synchrotron and tuned circuit) for the electrons to lose energy into a thermal reservoir at 4.2 K. The dependence on the total number of particles is a manifestation of the differing heat capacities of the electron and antiproton clouds. These rate equations must be solved numerically due to the complicated dependence of τ_c on T_p and T_e.

The simplest experimental arrangement is to rely only on synchrotron radiation to couple energy out of the electron cloud. This does not require any tuned circuits for the electron motion. The time constant for electrons in a 6 Tesla field is $\tau_c = 0.1$ s. The coupling of the electron cyclotron motion to the axial motion has been observed [5] to be much less than this for $N_e \geq 10^4$. The addition of an axial tuned circuit could shorten τ_e by a factor of 2, but it is most likely not necessary. Figure 4 demonstrates the effect of insufficient numbers of electrons which leads to heating of the electrons and a reduction in the cooling rate. The three curves shown are for different ratios of numbers of electrons to protons. Note that the curve for $N_e/N_p = 10^4$ is almost identical to fig. 3, where the electron temperature was fixed (infinite heat capacity in the electron reservoir). As the ratio of electrons to protons is decreased the cooling time becomes significantly longer. This is due to the increase in the temperature of the electron cloud. The maximum temperature of the electron cloud rises from 400 K to 9700 K when the ratio of electrons to antiprotons is decreased from 10^4 to 10^2. It is apparent that 10^4 electrons per antiproton is sufficient so that the cooling time is not limited by electron temperature at an electron density of $10^7\,\text{cm}^{-3}$. At higher

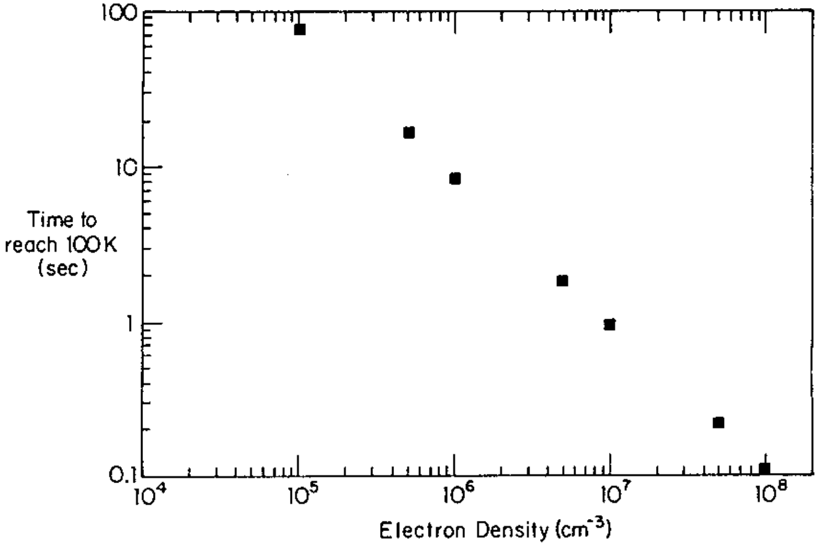

Fig. 5. Electron cooling time versus electron density. The time required to cool antiprotons from 1 keV to 100 K is plotted versus electron density.

density the coupling of energy from antiprotons to electrons becomes faster than the coupling of energy out of the electron cloud. The number of electrons needed so that the electron temperature is not a limiting factor is increased.

Since τ_c has a complicated dependence on T_p, the cooling time is not linearly dependent on the initial energy. The time to cool to 100 K increases from 1 s at an initial temperature of 1 keV to 25 s for a starting temperature of 10 keV. This is due to the v_{rel}^3 dependence of τ_c. Trapping and cooling in a short time at these higher energies requires dense electron clouds to increase the cooling rate, and large numbers of electrons to keep the electron cloud temperature from being a limitation. There is a strong inverse dependence on electron density as shown in fig. 5. From these rate calculations it seems that cooling from 1 keV to less than 100 K in 1 s or less can be expected with reasonable electron densities ($n_e = 10^7$ cm^{-3}) and total number, while relying only on electron synchrotron radiation to remove energy from the composite system.

Electron beam cooling in storage rings has demonstrated a large increase in cooling rates when a longitudinal magnetic field was applied. This has been referred to as fast or super cooling, and current electron coolers [10] are constructed with magnetic fields of ≈ 0.05 Tesla. One might expect a large effect in the 6 Tesla field environment of the Penning trap, but this is not the case. Fast cooling refers to the increase of the transverse cooling rate to nearly the longitudinal value when a magnetic field is applied. This arises because the longitudinal temperature of the electrons produced by an electron gun accelerated to high velocity is compressed, and is much smaller than the transverse temperature. In a magnetic field, the electrons become pinned to field lines, so that the particles in the storage ring have their transverse motion deflected into the longitudinal direction when they collide with the pinned electrons. The result is that the longitudinal cooling rate remains unchanged, but the transverse cooling increases. The electron pinning is even more extreme in the strong field of the Penning trap, but the longitudinal and perpendicular electron temperatures are equilibrated, since the electrons have many opportunities to collide with one another. There is no gain to be had, since the longitudinal and transverse rate are the same, with or without the field. However, the significantly lower electron temperature attainable in a Penning trap compared to an electron beam means there is no need to look for such an enhancement.

A possible difficulty in the application of electron cooling in a trap is centrifugal separation of the heavier antiprotons to the outside of the cloud, reducing the overlap between the cold electrons and hot antiprotons. In a Penning trap, both the electrons and antiprotons rotate at the same magnetron frequency, depending on trap potentials and space charge fields. The analogy to a centrifuge is apparent. It has been noted [14] that in equilibrium separation occurs only if the difference in the centrifugal barriers for the two species, $(m_1 - m_2)\omega_m^2 r^2$, is larger than the thermal energy, kT. There is one possible observation of such separation [15] in a two component system with laser-coled Be^+ and Hg^+. If the separation condition is evaluated, one finds that the different in centrifugal barriers was ≈ 2.5 K, while the ion temperature was ≈ 1 K, so separation was certainly possible. In the case of antiprotons and electrons, the difference in centrifugal barriers is ≈ 1 K. Separation should not be a problem, especially at the much higher temperatures where the electron cooling is of the most benefit. The radial transport is very strongly suppressed due to the difficulty in moving a charged particle across field lines in a strong field.

6. Conclusion

Most experiments planned with antiprotons stored in an ion trap will require a tuned circuit for particle detection. It would be convenient if the coupling to the tuned circuit was strong enough to rapidly cool the particles from the keV energies where they are captured, down to the low temperatures where experiments are planned. Unfortunately the cooling time is greater than 10^3 s, for reasonably sized traps. The minimum size trap is limited by the capture process, so the coupling cannot be increased arbitrarily by using a very small trap with high potentials. It is important to recall that the c-m motion of a cloud cools much more rapidly than a single particle, but the total energy of the cloud decays with the single particle time constant, as long as the cooling is not limited by transfer of energy out of the internal motion to the c-m motion.

Negative feedback methods, both continuous and pulsed (stochastic), can reduce the cooling time. The feedback effectively reduces the single particle time constant, toward a limit due to the coupling between the c-m motion and the internal degrees of freedom. These methods are likely to become more difficult as the gain is increased, limiting the reduction of the cooling time. In addition, the final temperature reached is proportional to the gain, so the gain must be reduced as the particle cooled, increasing the cooling time. Both resistive cooling and negative feedback methods are sensitive to bandwidth limitations and place severe demands on the harmonicity and size of the trap. The shortest time constant possible using negative feedback for a cloud of trapped particles is N times the coupling time between the internal degrees of freedom and the c-m motion when a high gain is used, making this technique less useful for increasing numbers of particles. This coupling, due to trap anharmonicity, cannot be arbitrarily increased, due to the harmonicity requirements of the narrow band detection. In addition, as the particles cool, the coupling decreases as the particles spend less time in anharmonic regions. This probably necessitates increasing the trap anharmonicity as the cooling proceeds. This technique, whether applied continuously or as stochastic cooling, is most advantageous when the single particle time constant is very large, as would be the case in a large trap designed to capture many antiprotons.

Adiabatic cooling can be quite effective and is simple to apply. It can only be used when the particle energy is much less than the well depth. This restricts the usefulness of this technique, which is not applicable when the antiprotons are first trapped and have energies comparable to the well depth. An additional disadvantage of adiabatic cooling is that it increases the amplitudes of oscillation of the particles. Adiabatic cooling of the cyclotron motion is difficult because of the persistent mode superconducting magnets used for these experiments, and precluded because of the desire for as large a magnetic field as possible.

Collisional cooling of the antiprotons with energy-transferring collisions to a simultaneously trapped cloud of electrons is very promising. The cooling time can be approximately 1 s for a reasonable electron density of 10^7 cm^{-3}. It is important that there are many ($\approx 10^4$) electrons per antiproton so that the cooling process is not limited by an increase in electron cloud temperature. This cooling time is obtainable without the need of any tuned circuit for the electrons, since the synchrotron radiation of the electrons transfers the energy out of the system. It may be desirable to confine the electrons to a smaller region than the antiprotons. In this case the cooling rate is lowered by the fraction of time the antiprotons interact with the electron cloud. Electron cooling has the attractive features of acting on the total energy of a trapped cloud of antiprotons, with no limitation due to energy transfer between internal and c-m motion, and it involves no resonant frequencies, reducing the requirements on the harmonicity of the trapping well.

In the antiproton mass measurement experiment multiple types of cooling will probably be employed. Electron cooling would be used initially while the antiprotons are undergoing large oscillations, to reduce the energy far below the trap well depth. The high voltage on the endcaps needed for capture could then be lowered adiabatically to the value required for the precision work, with a substantial amount of adiabatic cooling. The tuned circuit required for particle detection can then remove the small amount of remaining energy, and cool the antiprotons into thermal equilibrium at 4.2 K.

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