Chapter 6

Accumulating positrons

Due to the stability of particle motions in a Penning trap and the ultra-high vacuum conditions in the trap can, positrons can be accumulated and stored for days, weeks, or even longer. We have already demonstrated accumulation of more than 36,000 positrons in 52 hours (Section 6.1), and we anticipate that substantially larger numbers are feasible. In Section 6.2 we discuss the expected storage capacity and positron lifetime limits for this trap.

6.1 Loading rate independence of accumulation time

We verify that the positron trapping rate is constant for accumulation times of less than a few hours by counting the number of positrons loaded as a function of accumulation time. An example of this is shown in Fig. 6.1. In this case, the trap was emptied after each measurement. For accumulation times of longer than a few hours, we periodically move the loaded positrons to the trap center without emptying the trap.

The results of our longest positron accumulation run to date are shown in Fig. 6.2. Every four hours the mechanical beam shutter was closed, the resonant

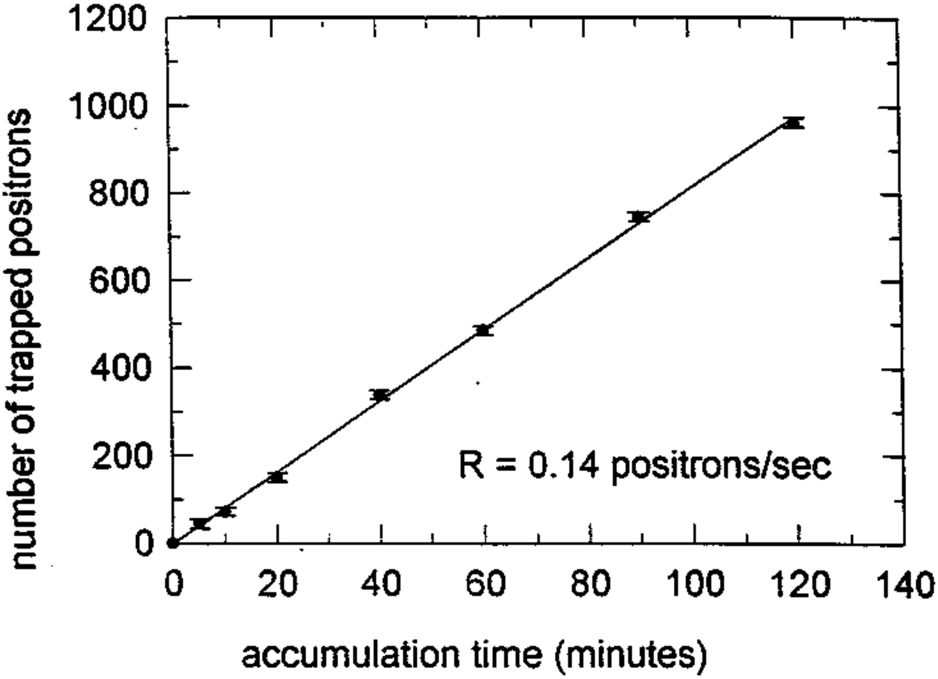

Figure 6.1: Positrons are loaded into the trap at a steady rate, independent of accumulation time between magnetron cooling sweeps, for accumulation times of at least 2 hours and possibly much longer. The trap was emptied at the end of each measurement. In this example, the loading rate was 0.14 positrons per second.

ion drive was turned off, and the accumulated positrons were moved to the trap's center and counted. Then the ion drive was resumed, the beam shutter was reopened *without* dumping the accumulated positrons, and loading continued for another four hours. This cycle was repeated until the total accumulation time equaled 52 hours. Positrons accumulated steadily at a rate of 0.2 positrons per second, resulting in more than 36,000 trapped. The noise spectrum of this cloud is shown in Fig. 6.3. (The different loading rates between Fig. 6.1 and Fig. 6.2 are due to differences in moderator preparation.)

When the number of trapped positrons exceeds 10^4, it is necessary to make two modifications in the magnetron cooling and counting procedures. First, the axial

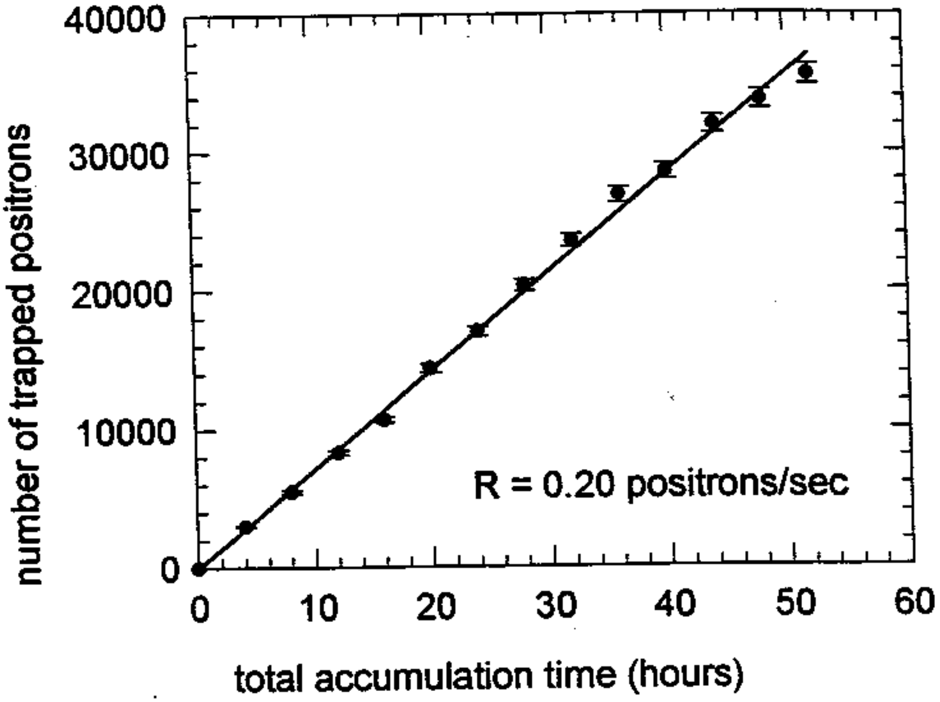

Figure 6.2: Results of the longest accumulation run to date. Positrons loaded at a constant rate of 0.20 positrons per second for 52 hours.

frequency ν_z of these large clouds is noticeably different from that of small clouds or a single positron. This is because larger clouds sample more of the inhomogeneities in the trapping potential. It is therefore necessary to slightly adjust V_{ring} during the magnetron cooling sweep to bring the axial frequency of large clouds back into resonance with ν_{LC} as positrons accumulate. Secondly, as the width of the "dip" in the noise spectrum becomes larger than ν_m, it is necessary to shift the frequency of the cooling drive so that the cooling drive does not resonantly drive the cloud's axial motion. For example, if the width of the positron dip is 50 kHz, the cooling drive should be set at $\nu_{\text{drive}} \simeq \nu_z + \nu_m + 20$ kHz (where $\nu_m \simeq 14.4$ kHz) so that the drive frequency is greater than the frequency spanned by the dip while the "response spike" at $\nu_{\text{drive}} - \nu_m$ lies within the dip. In this way, the entire positron

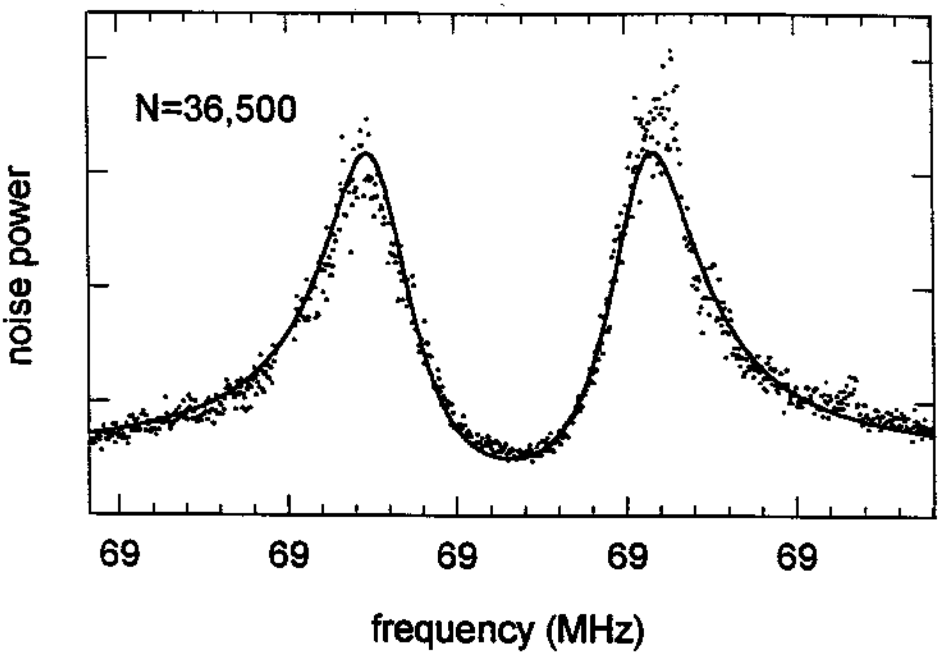

Figure 6.3: Noise spectrum of the largest positron cloud obtained to date, more than 36,000 positrons. The dark line is a fit to the theoretical lineshape.

cloud is magnetron cooled without resonantly driving its axial frequency. Further slight modifications in the magnetron cooling procedure may be necessary when the number of trapped particles exceeds 5×10^4, since the width of the "dip" in the noise spectrum will exceed the width of the LRC damping circuit. We plan shortly to begin tests by loading and centering large, off-axis electron clouds, to insure that we can magnetron cool large positron clouds without loss.

6.2 Expected limits on positron storage

There are a number of mechanisms by which positrons could be lost from the Penning trap [1]. The first we consider is radial transport of positrons out of the trap due to collisions with background gas atoms [58]. Small-angle collisions with background gas atoms cause trapped positrons to diffusively increase their magnetron radius until they exit the trap. However, this process is unimportant for us because of the extremely high vacuum conditions. Moreover, any radial diffusion of the cloud can be overcome by applying a magnetron cooling drive. The second loss mechanism for positrons is by annihilation with electrons in the background gas atoms. This can happen either by direct annihilation, or—if the positron has sufficient kinetic energy—via positronium formation. We consider these two separately.

Positronium formation can happen only when the positron has kinetic energy greater than $E_i - E_{\mathrm{Ps}}$, where E_i is the energy required to ionize the molecule and $E_{\mathrm{Ps}} = 6.8$ eV is the binding energy of positronium. At 4 K the dominant background gas should be helium. The cross section for positronium formation on helium (when the positrons have sufficient kinetic energy) is known to be [59,60]

$$\sigma_{\mathrm{Ps}} = 0.16\pi a_0^2, \tag{6.1}$$

where a_0 is the Bohr radius. Because of the ultra-high vacuum conditions in our trap can and because the kinetic energy of each positron is damped to below 1 eV rapidly (< 1 second), after which positronium formation is energetically impossible, this is not a significant loss mechanism in our trap.

Once positrons have cooled below energies for positronium formation, only direct annihilation with electrons in the background gas atoms is possible. The effective cross section for direction annihilation is given by [59,61]

$$\sigma_{\mathrm{eff}} = \pi r_0^2\, c Z_{\mathrm{eff}}/v, \tag{6.2}$$

where $r_0 = 2.8 \times 10^{-13}$cm is the classical electron radius, c is the speed of light, v is the velocity of the positron. and $Z_{\mathrm{eff}} = 3.94$ for helium. The expected lifetime of a trapped positron at 4 K is therefore

$$\tau = \frac{1 -}{n v \sigma_{\mathrm{eff}}} \simeq \frac{3.4 \times 10^{13}\ \mathrm{sec}}{n} \tag{6.3}$$

where n is the number of background helium gas atoms per cm^3. At 5×10^{-17} Torr and 4 K, $n \simeq 10^2$ which gives a positron lifetime longer than the experimenter's.

If positron loading were continued indefinitely, we would eventually reach the storage capacity of the Penning trap. The capacity of a Penning trap is a function of its physical size and the strengths of the electric and magnetic fields. In principle, the positron density limit is determined by the Brillouin limit [62,63,64], when the particles' radial motion becomes unstable because of the large radial electric field due to space charge. This limit can be written as

$$n_{e+} < 4.8 \times 10^{12} \left(\frac{B}{1 \text{ Tesla}} \right)^2 \quad (cm^{-3}), \tag{6.4}$$

where B is the magnetic field in Tesla and n_{e+} is the number of positrons per cm^3. In practice for these traps, the density limit is also determined by the particles' space charge potential in the axial direction. Consider a spherical cloud of radius L of N_{e+} positrons. The electric potential at the edge of the cloud due to space charge is (in S.I. units)

$$\phi_{e+} = \frac{e^2 N_{e+}}{4\pi\epsilon_0 \, L}, \tag{6.5}$$

which must be counter-balanced in the axial direction by the trap's electrostatic potential. Assuming a uniform density of positrons in our trap (with hyperbolic electrodes) yields

$$n_{e+} \simeq \frac{10^7 \; V_0}{1 \;\; \text{Volt}} \quad (cm^{-3}). \tag{6.6}$$

Since the trap has a volume of slightly less than 1 cm^3 and typically operates at $V_0 \approx 10$ Volts, our storage capacity is approximately 10^8 positrons. Accumulating 10^8 positrons at 0.2 per second would take 16 years. With significantly increased loading rates, it may become desirable to accumulate still greater numbers. This could be accomplished by drilling a larger hole in the center of the endcap electrodes and periodically moving positrons from the loading trap into another storage trap which could be operated at higher containment voltages. A Penning trap at U.C. San Diego operating at several kilovolts has achieved 10^9 trapped electrons at a density of 2×10^{10} electrons per cm^3 [63]. Therefore, the storage capacity of these traps does not currently limit positron accumulation, and is more than adequate for the applications outlined in Chapter 7.