Chapter 7

Protons

Trapping protons (and other positive ions) in a Penning trap differs from trapping electrons in several ways. First, the polarity of the dc trapping potential must be reversed from that used for electrons. Second, many positive ions can be trapped with the protons, while pure electron clouds are almost unavoidable since negative ions are difficult to form. Third, damping is less effective for the heavier protons since resistive damping scales as $1/m$ and synchrotron damping of the cyclotron motion goes as $1/m^3$.

7.1 Loading Protons and Other Positive Ions

Several methods have been used to load protons and other ions into a Penning trap. The simplest method is to use electron bombardment to ionize background neutral gas which is present or injected into the trapping region. In our case, the electron source is a field emission point produced by etching a 0.5 mm diameter tungsten rod in a sodium hydroxide solution. Typical bias voltages between the point and grounded electrodes approximately 0.5 cm away range from -150 to -2500 Volts depending upon the sharpness of the point. Emission currents can be controlled between 0.01 nA and 1 μA.

For experiments at room temperature, the pressure is sufficiently high that protons or other ions can be loaded directly from the background gas. For this cryogenically cooled experiment, the pressure is very low (less than 10^{-16} Torr) so that this is not possible. Since the number of particles needed is small, it is sufficient to generate common ions by first dislodging adsorbed neutral gas from a trap electrode surface using electron bombardment and then ionizing it within the trap. The small inner trap lacks a surface perpendicular to the 5.9 T magnetic field (Fig. 3.1), making loading protons and other ions difficult. In an earlier trap configuration, electrons struck a hydrated titanium disk at the end of the lower endcap. In the present trap, configured to load antiprotons and interfaced to LEAR, electrons instead strike the gold-plated aluminum degrader located about 4 *cm* from the center of the harmonic well (Fig. 3.4). Both surfaces are a sufficient source of neutral hydrogen, most likely originating from organic compounds.

There are two main problems with obtaining ions from the residual neutral gas content on the degrader surface. First, many other ion species are generated other than H^+, predominantly carbon, oxygen, and nitrogen. Second, the electron beam only strikes a very small region. Since the degrader surface is at 4 K there is likely little surface migration of adsorbed gases and the source becomes less effective with time. As the source depletes, additional gas can be generated with a higher field emission current which increases exponentially with applied bias voltage.

7.2 Axial Signals

In principle, the axial detection of protons is the same as for electrons discussed in Chapter 6. Because of the larger mass, the resistive damping time (proportional to q^2/m) of the proton is slower than the electron by a factor of m_e/m_p.

Figure 7.1(b) shows a proton signal superimposed on the noise resonance, quite analogous to Fig. 6.1(b) showing the electron dip. The striking difference is that instead of observing a dip, we observe a peak even when the motions are not driven. Given enough time, this peak will damp down so that it is not visible with respect to the noise resonance, though we do not see the proton signal as a dip. Modeling the protons as a series *lc* circuit [115], the proton reactive impedance as a function of frequency is approximately $[i2\pi(\nu-\nu_z)md^2/ne^2]$, where $i=\sqrt{1}$ and n is the proton number. On resonance, the protons are an effective shunt, but the linewidth will be more narrow and difficult to resolve than for electrons.

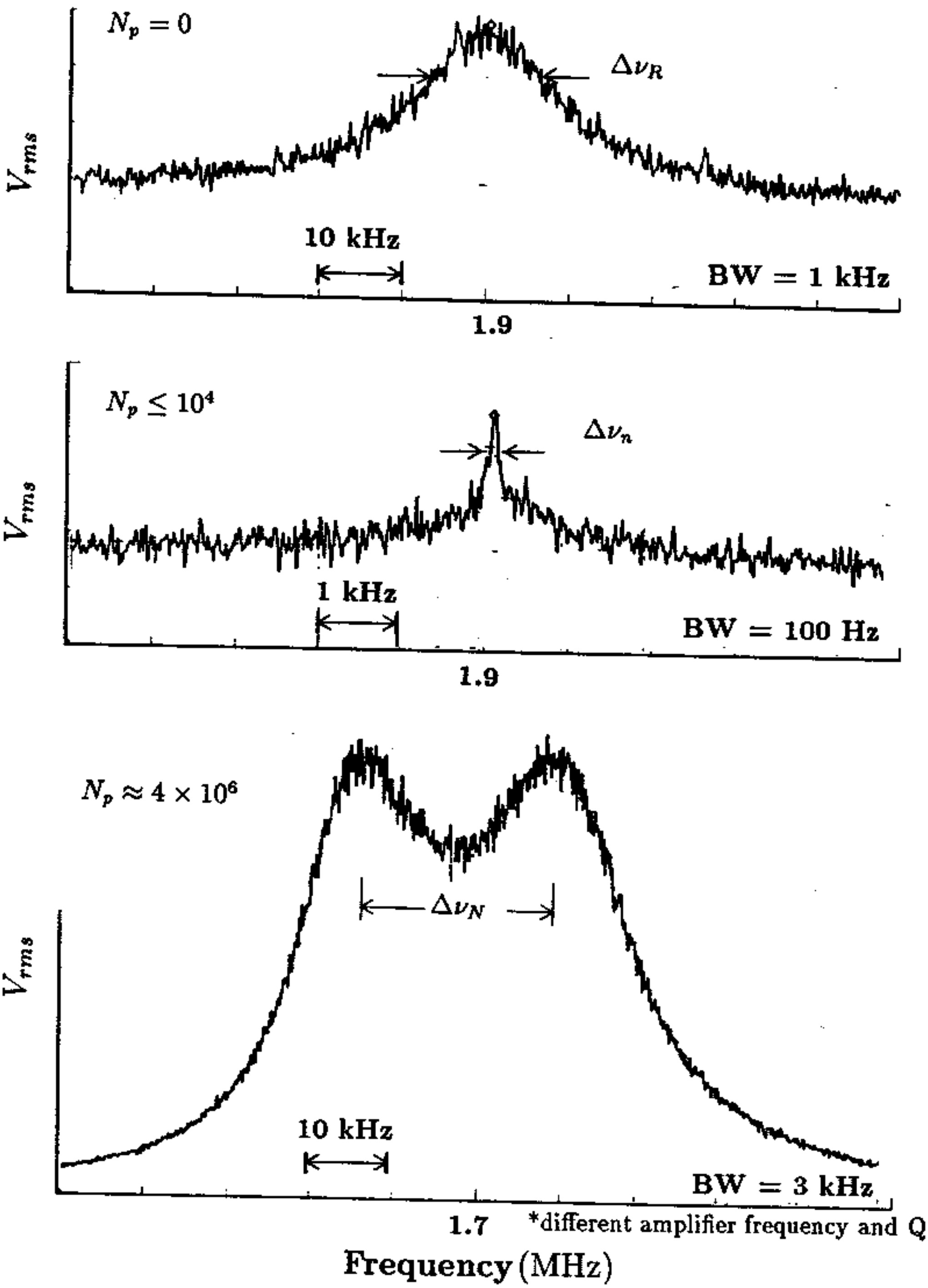

Figure 7.1: The voltage induced across the resonant tuned circuit at the proton axial frequency with (a) no protons loaded, (b) a small number of protons in the trap, and (c) the response resulting from an extremely large proton cloud. Note the difference with Fig. 6.1 for electrons.

Protons and other ions appear as a peak because they are much hotter than the tuned circuit, unlike electrons which damp much faster by synchrotron radiating to the 4 K environment. The peaks are reflective of the higher energies the protons are and how much more difficult it is to remove energy from them. At normal trapping frequencies, protons are only resistively damped. In addition, other ions may be in the trap and not on resonance with a detection amplifier. For such ions, not even resistive damping exists and the only way to damp their motion is by collisional coupling to the resistively cooled protons. These collision coupling times are typically quite long.

Electrons can also be seen as a peak if a sufficient heating source is provided to overcome the much faster synchrotron and resistive damping. (For example, Fig. 8.1 shows axial electron peaks in a mixed electron-antiproton cloud, where the electron axial motion is continuously heated by strong antiproton cyclotron excitation.)

In the case of very large proton numbers we observe the signal shown in Fig. 7.1(c). The two peaks correspond to the parallel resonances formed when the reactance impedance of the proton cloud is nearly equal and opposite to the impedance of the detection LC circuit. (Compare with Fig. 6.1(c) for electrons).

7.2.1 Identifying Ions

In Fig. 7.2(a) we identify a series of ions by detecting their axial motion after loading the trap using a typical field emission current (20-200 nA for protons as compared with 1 nA for electrons). For this particular field emitting point we applied a potential of -1.8 kV. The vertical axis in Fig. 7.2 is the square law output in a detection bandwidth of 1 kHz at $\nu_z \approx 1.9$ MHz. As the trapping potential is swept from -50 to -250 Volts, ions with different charge to mass ratios are brought into resonance with the tuned circuit and are observed in the detection window. Many single charged heavy ions are not visible on this scan. For our trap it would require a potential > 300V (the maximum we were able to put on the filter capacitors) to make their axial frequency resonant with the 1.9 MHz detection circuit. The observed signal is dependent upon particle number, particle

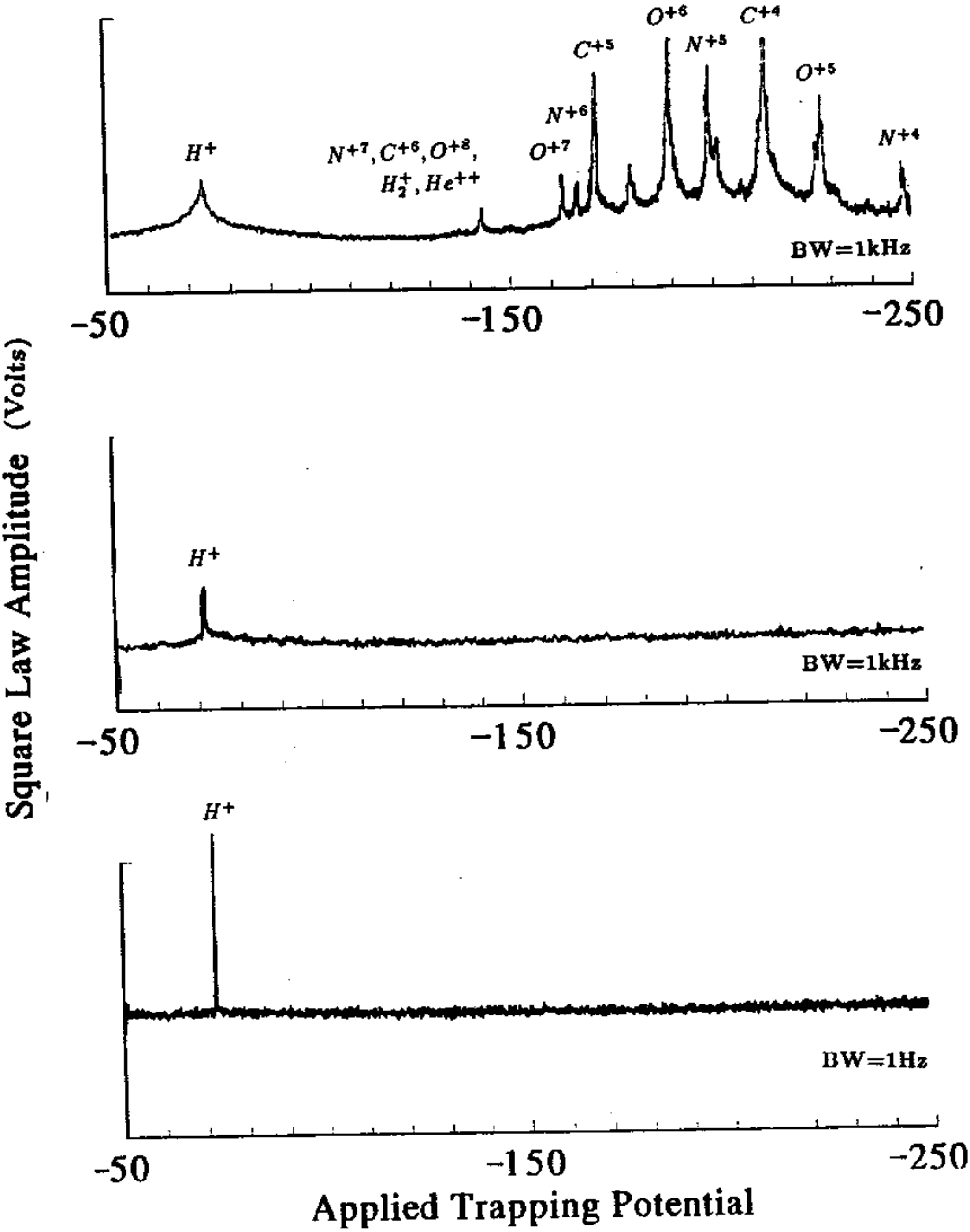

Figure 7.2: Axial signals of identified positive ions (a) loaded with high energy nested electrons, (b) loaded with lower energy nested electrons, and (c) after applying a noise broadened axial drive sequence to the unwanted ions during loading.

axial temperature, observation bandwidth, and sweep rate. Highly stripped ions are energetically possible because 2 keV ionizing electrons are obtainable from this particular FEP.

Assuming the particle species are highly coupled and in thermal equilibrium as we expect for this large cloud of ions, the amplitude of each ion type is a measure of the relative composition of the confined cloud if the detection sensitivity for each type is taken into account. The spectra displayed in Fig. 7.2 were generated from electron bombardment of the gold plated aluminum degrader. Other targets generate different compositions. For example, a hydrated titanium foil produced higher proportions of protons to other ions, but other ions were still present.

The axial signals can easily show very small amounts of helium and therefore can be used for sensitive detection of leaks. In most cases with the present detection sensitivity, He^{++} and He+ axial signals are not observed even though a 5×10^{-9} Torr partial pressure has been identifiable with an Ametek quadrupole gas analyzer during pumpout of the vacuum enclosure with a turbomolecular pump. (An ion pump was also active in the system and the trap enclosure was at 120°C at the time of the measurement.)

7.2.2 Coupled Cyclotron Observations

The multiple ion system provides an opportunity to measure the cyclotron frequency of several ions by a bolometric (or heating) technique. Axial heating can be observed as a function of the cyclotron excitation frequency. The technique is analogous to the more sensitive technique of observing the electron cyclotron frequency but relies on collisional coupling to transfer energy of the exited cyclotron motion into its axial motion (or into the axial motion of another species).

A valuable application is for indirect cyclotron measurements of ions not accessible in the range of existing detection amplifiers. A major limitation with this technique is that the only damping available for such ions is by the same indirect coupling mechanisms so that damping can be very slow. In Fig. 7.3 we show typical bolometric axial observations as a function of cyclotron heating of H^+, O^+4, and several carbon ionization states. The mass ratios determined from the data

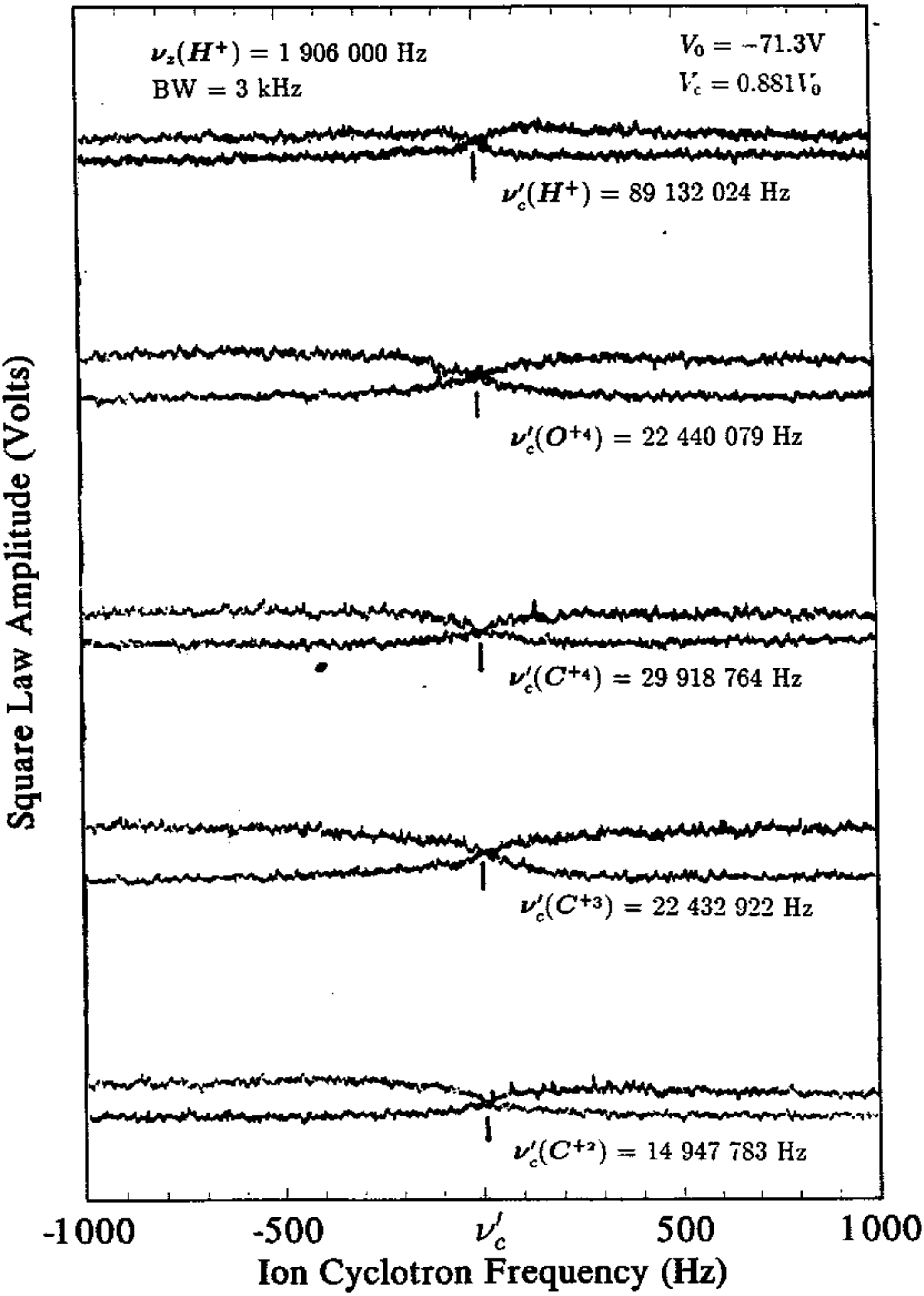

Figure 7.3: Ion cyclotron resonances of ionized hydrogen, oxygen, and carbon as observed through the axial heating of the proton axial motion. All traces are from the same confined cloud.

in the figure are

$$m(O^{+4})/m(p) = 15.877\,208(36)$$
$$m(C^{+4})/m(p) = 11.911\,148(20)$$
$$m(C^{+3})/m(p) = 11.911\,704(36)$$
$$m(C^{+2})/m(p) = 11.912\,252(40),$$

where the uncertainty given reflects only the observed resolution of approximately ± 50 Hz. Our measured value of $m(C^{+4})/m(p)$ is 1.1×10^{-6} higher than the more accurate measurement reported by Moore et. al. [72]. The frequency measurements require strong resonant drives at ν_c' and a shift to lower frequencies is in general observed for increased heating. The 'crossing' signature in Fig. 7.3 reflects the long damping time of the ions and results in a lineshape that is difficult to interpret to high precision. (The effect of heat on the cyclotron lineshape and the heat dependent shift become more apparent using direct detection techniques as shown in Fig. 10.13). Even though resolutions approach 10^{-7} with this technique, energy dependent systematic shifts limit achievable accuracies to about 10^{-6}. An important use of this coupling scheme will be discussed in Chapter 8 using the unique two component system of antiprotons and electrons. Unlike the positive ion system mentioned here, we will then be aided by the ability of the electrons to synchrotron radiate much of the energy and keep the antiproton energies low, yet allow for collisional coupling to be effective.

7.3 Eliminating Contaminant Ions

For the highest precision measurements on protons, it is necessary to eliminate all other ions from the trapping region. In this section we summarize a few of the avenues that we have explored.

Single Ion Source

One possible way to obtain a single species cloud is to load from a specific gas let into the trapping region. Because of the initial uncertainty on the achievable antiproton lifetime, we did not want to risk compromising the vacuum in our trap vacuum enclosure by adding H_2 neutral gas. Such gas would be only weakly cryopumped, and we had the concern of pressure surges during antiproton loading that might result in high annihilation rates for low energy antiprotons.

Instability of Very Small Traps

A Penning trap can be made unstable if the radial component of the electric field is large enough to overcome the radial binding due to the magnetic field. The potential needed to exceed the stability condition $\nu_z < \nu_c/\sqrt{2}$ depends on the size of the trap. Our open endcap trap could be made stable for only protons, but unstable for all heavier ions if we applied 18 keV. This potential is not possible to achieve on our trap because of small tolerances and the presence of sensitive detection electronics. However, for much smaller geometries, potentials required for instability are more accessible. We have constructed a trap with an effective trap dimension of d = 0.12 cm. In principle, only protons will be stable with an applied potential of 1100 Volts in the 5.9 T field. In order to make room for the long trap for loading antiprotons this trap is presently incorporated into the trapping scheme described in Chapter 3, and its usefulness for ion work still remains to be demonstrated.

Ionizing Electron Energy and Nested Traps

The number of multiply stripped ions can be reduced by keeping the electron beam energy lower than most ionization thresholds. The field emission point most frequently used emits about 1 nA at -1600 Volts. To increase the loading efficiency, yet reduce the number of multiply stripped ions, we load the trap in a low energy nested well configuration as shown in Fig. 7.4.

Figure 7.2(a) and (b) shows ions trapped when the outer trap has a depth of -1600 Volts (Fig. 7.4(c)) and -100 Volts (Fig. 7.4(d)). In both cases the incident electrons have a kinetic energy of 1800 eV. Without the nest each emitted electron only passes through the trap once. With the nest, primary and secondary electrons are confined increasing the probability of ionizing neutrals. High energy electrons generate neutrals from the degrader surface (most likely by local heating), yet the

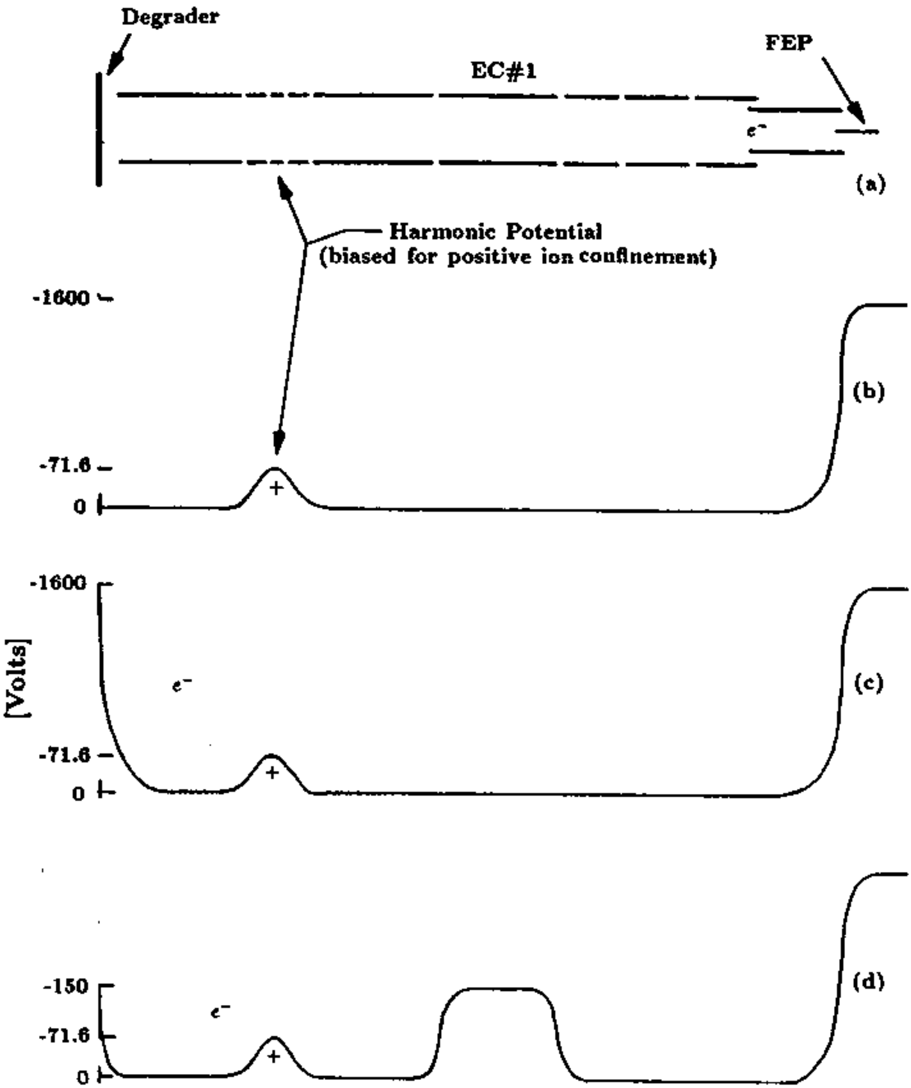

Figure 7.4: Nested trap configurations for energy selection of loaded ions.

ionizing seems dominated by the low energy nested electrons (which have higher cross sections and multiple passes). Ideally the ionizing electron beam could be reduced to near 13.6 eV, the binding energy of hydrogen. Most other ions would not be formed since only a few have ionization potentials smaller than this energy. At the present, effective loading requires a minimum of 70 Volts between the applied outer trap potential and the harmonic well bias (7.4(d)).

Resonance Ejection: Noise Broadened Excitation Drives

Several trapping groups have found that driving on the resonant frequency of the ion can be an effective way in reducing unwanted ions from being confined in the trap . Two techniques have shown promise. Church and coworkers have applied ν_c' and ν_m excitation during the loading process to only allow specific charge to mass ratios to fall into the trap [55,20]. Other groups [72,21] have had success with cleaning techniques applied after the trap is loaded by applying strong noise broadened axial excitations to drive the axial amplitude into the endcap of a traditional hyperbolic trap. The noise broadening is needed to take account of possible amplitude dependent changes in ν_z due to trap anharmonicity. Since our trap endcaps have no surface perpendicular to the trap axis we have found it difficult to resonantly drive ions out once they have been loaded.

In our trap, the use of very strong noise broadened axial excitation drives to the unwanted ions *during* the loading process has proven to be effective. We use a white noise source from a HP 3561A signal analyzer to FM modulate the selected axial drive frequency generated by an HP 8662A frequency synthesizer. A 30 kHz modulation and an axial drive amplitude of -10 dBm is applied to a trap endcap.[1] The effectiveness of the technique seems dependent on the proper amplitude (too strong keeps the protons from loading, too weak allows other ions to load). During the loading process, we repeatedly step through the various axial frequencies of possible contaminant ions, each for a duration of 1 second. For loading protons, we pass the drive through a 1.2 MHz low pass filter to avoid harmonics of the strong

[1]Helpful suggestions for effective noise broadening and drive amplitudes were provided by W. Jhe and D. Phillips.

drive form overlaping with the protons. When ions are first formed in the trap, they are only weakly bound and the strong noise broadened drive is sufficient to prevent the ion from damping and staying bound. By concentrating on the parent ions of more highly stripped ions (O^+, N^+, C^+), we prevent most contaminants from loading.

The results of applying this technique are shown in the potential scan shown in Fig. 7.2(c) using the configuration in 7.4(d) with the noise broadened drive added. The cleanliness of the proton cloud is verified in two ways. First, the contaminant level is low enough that we not able to observe heating of the proton axial and/or cyclotron motions by driving hard on the cyclotron frequency of the undesired ions. Second, we can obtain coherent axial resonance signals which appear to only be possible in a single species cloud.