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REMOTE ANTIPROTON SOURCES

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Summary

Antiprotons are well on their way to becoming a standard laboratory commodity. Heavy utilization of LEAR is ushering in a new era where $\bar{p}$'s achieve their logical potential, equal to that of e^-, e^+, H^-, as controlled probes and experimental building blocks. The uniqueness and usefulness of $\bar{p}$'s for studies at low (table top) energies is well documented.[1] The main stumbling block to universal pursuit of such studies is the overhead of $\bar{p}$ production. The stability of the $\bar{p}$ thus makes cogent an investigation of possibilities and limits to transporting $\bar{p}$'s in quantity.

I will base my discussion on LEAR as the source of $\bar{p}$'s for bottling, since it is the only concrete example to work with at present. Two other lines of contemporary research then, largely in atomic physics, pioneered by Dehmelt and collaborators, aimed at precision studies of clouds of, or single $e^{\pm}, p^{\pm}$, or ions in large storage time traps.[2] Second, there is work, experimental and theoretical, from the plasma physics tradition aimed at characterizing non neutral plasmas.[3]

The Quadrupole Penning Trap

The highest precision studies to date on $e^{\pm}$ and protons have been conducted in Penning traps (electrostatic axial confinement; magnetic radial confinement; overall cylindrical symmetry) with quadrupolar electrostatic fields.[2] Such a trap, designed for precision single electron work, is shown in Figure 1. Such traps are used in sealed containers at 4.2° K (the $e^{\pm}$,p sources being internal) providing immeasurably high vacuua.[4] Electrons are stored for indefinite periods (≈year observed) with no perterbation. This is a crucial point for $\bar{p}$ storage since the p capture on background gas cross section is divergent in the limit $T \to 0$.[5] For instance, $P \approx 10^{-14}$Torr would limit storage half life to one day.

The basic question of $\bar{p}$ bottled lifetime will be answered by an experiment now approved to run at LEAR before the ACOL shutdown. Antiprotons, fast extracted from LEAR at 5-20 Mev, will be degraded by a Beryllium foil which doubles as the end window of a 4.2° K Penning trap. In this way up to ~100's of $\bar{p}$'s should be trapped. Note that single protons have been detected, cooled and manipulated in similar traps.[6]

Particles initially injected into a trap are "hot" ($T \gg 4.2°$ K) and must be cooled either for precision studies or for cyclic accumulation of high density clouds. Traditionally this occurs by radiative cooling (for $e^{\pm}$) of the cyclotron motion and external resistor damping (see Fig. 1) of the axial motion.[2] For modest density clouds the axial and cyclotron motions are known to be coupled on a short time scale(< 1 sec). Unfortunately the coupling to an external resistor is inversely proportional to the axial SHO resonance line width and mass. Cloud space charge distorts the Quadrupole field, spoiling the effective oscillator Q. Hence build up of dense $\bar{p}$ mass clouds becomes too slow by these methods.

Instead, initial $\bar{p}$ temperatures of ≈few Kev will be electron cooled.[7] An internally generated, cold, electron cloud is easy to maintain at trap center. Calculation predicts initial damping rates >10/s for 3 Key $\bar{p}$'s moving through $n_{e^-} = 10^7 cm^{-3}$(easily achieved in practice).

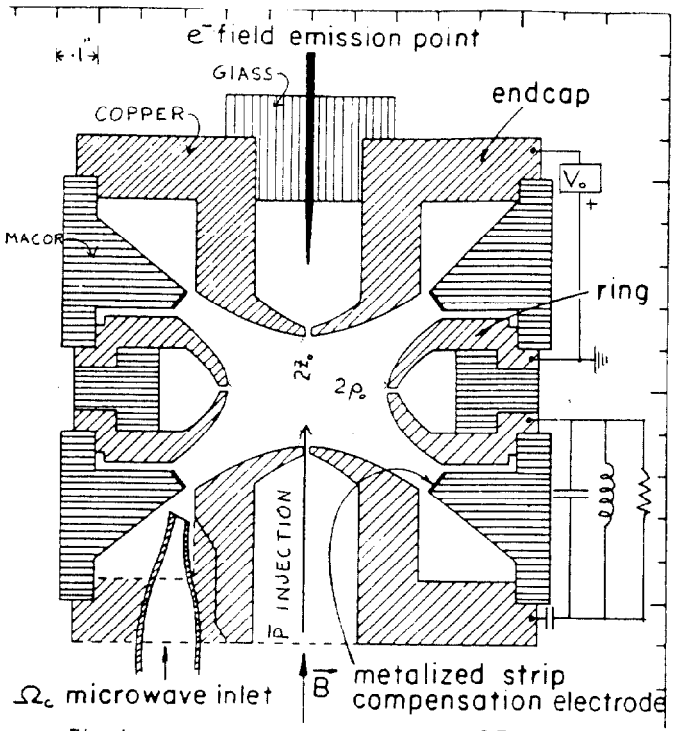

Fig. 1 experimental e^- Penning trap[2,7]

Limits to Bottled p Number and Density

In this section I restrict discussion to p capacity of the Penning trap itself. The highest stored p numbers, N_{max}, will require cyclic accumulation in an open (to beam line) trap. Limitations associated with accumulation are deferred to the next section.

The trap potential well is, for the standard aspect ratio trap ($\rho_0 = \sqrt{2}\, z_0$)

$$V_T(\rho,z) = \tfrac{1}{2} V_0 (z^2 - \rho^2/2)/z_0^2 \qquad (1)$$

I summarize in table 1 the properties of a small precision work trap (figure 1) scaled up to a size approaching the practical limit of what may be considered portable. LEAR can provide a small spot size at the trap (≈1mm ϕ), which is initially preserved by the strong trap field. (r_c < .2mm). This requires only a similarly small electron cloud to accomplish fast electron cooling.

Eventually all antiprotons come into temperature equilibrium at 4.2°K. By temperature equilibrium we refer to the cyclotron and axial degrees of freedom. Azimuthal ("magnetron") motion is essentially constrained by canonical angular momentum, it being unstable radially.[2] For the electrons this canonical momentum and hence the cloud radius can be externally manipulated at will ("magnetron cooling").[2] For the $\bar{p}$'s a natural ellipsoidal equilibrium cloud shape is arrived at.[8] For densities 10^6 $\bar{p}$ /cm³ this cloud has well defined edges (falling of in λ_D <<1mm) inside of which the density is constant.[9] The unique shape and essential stability of such cold clouds is to be emphasized: intra beam scattering cannot increase the equilibrium cloud dimensions.

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TABLE 1: HIGH CAPACITY $\bar{p}$ BOTTLE PARAMETERS

PARAMETER	
z_0	10 cm
ρ_0	14.1 cm
V_0	28 Kv
V_F ($\Delta V \equiv V_0 - V_F$)	25 Kv
τ	100 ns
B (solenoidal)	7 T
r_c (cyclotron radius $\bar{p}$)	.68 μm
r_c(cyclotron radius e^-	80 Å
N_{max} ($\approx V_0 z_0/e$)	1.7×10^{12}
$n_{\bar{p}max}$	$\geq 2\times10^{9}$ cm^{-3}
Brioullin Limit ($\bar{p}$)	1.3×10^{11} cm^{-3}
T (cold cloud temp.)	<5 °K
λ Debeye ($n_{\bar{p}max}$ @ T)	3.2 μm
$\omega_{plasma}(n_{\bar{p},\ max})$	4.8×10^{8} rad/s
$\Omega/2\pi$($\bar{p}$)	1.9 GHz
E_0 ($\bar{p}$ Energy into trap)	20 Kev

Neglecting image charge fields the s.c. potential internal to the ellipsoid is

$$V_{sc}(\rho,z) = 4\pi n e(G_\perp \rho^2 + G_z z^2)$$

where $2G_\perp + G_z = 1$. Equilibrium demands $\frac{\partial}{\partial z}(V_{sc}(0,z) + V_T(0,z)) = 0$. This condition plus $N_{tot} = n\ 4/3\ \pi a^2 b$ determine the unique ellipsoid size (a & b) in terms of G_z and n. Note that the potential contour eccentricity does not exactly (approx. however) correspond to the ellipsoid eccentricity. Demanding a spherical distribution gives the characteristic constraint:

$$a/z_0 = \left(eN_{tot}/V_0 z_0\right)^{\frac{1}{3}} < 1 \qquad (2)$$

which is the condition that the axial potential well be destroyed by space change. V_0=28Kv and z_0=10cm gives this ideal limit of 2×10^{12} $\bar{p}$. However $a/z_0 \to 1$ cannot practically be approached for several reasons. Condition (2) is also roughly the criterion for image charge to become important. Its neglect overestimates the trap well depth. Further, during cyclical accumulation the lower, transient, V_{Fill} associated with $\bar{p}$ injection(next section) ought to be regarded as the limit for (2).

The criteria for radial trapping sets the Brioullian limit for magnetic field strength:

$$\omega_p^2 \leq 3(\tfrac{1}{4}(eB/mc)^2 - \tfrac{1}{2}eV_0/z_0^2) \equiv 3(\tfrac{1}{4}\Omega^2 - \omega_z^2) \qquad (3)$$

The magnetic term dominates for table 1 values. For V_0=1Kv,z_0=1cm., one has $n_{\bar{p}} \sim 1.5\times10^{10}/cm^3$. Such fields necessitate superconducting magnets, which have long been required in single particle precision work for different reasons.[2]

Accumulation Procedure

Fast extracted bunches from LEAR can be decelerated to within range of electrostatic final deceleration (trapping by either an auxillary low energy ring (ELENA[10]) or via RFQ. The feasibility of phase space preserving deceleration via RFQ from 5Mev to ≥10Kev has been checked and such a device is being developed for LEAR.[1] Therefore I assume use of an RFQ but note that it brings with it the complications of high frequency (200-400 mHz) prebunching (e.g. in LEAR) post debunching, and relatively poor pre-trap vacuum ($\geq 10^{-10}$ Torr!)

The general accumulation scheme is as follows: A length τ $\bar{p}$ batch is fast extracted from LEAR. This batch is decelerated to E= 20Kev in an RFQ, and proceeds via direct vacuum path through a small ($\lesssim$ 2mm ϕ) on axis hole in one endcap. If the trap voltage (endcap to ring) is $-V_F$ during this injection and the space charge depression is $+V_{sc}$(existing cold cloud) then V must be increased by 20Kev-V+V_{sc}in order to stop the $\bar{p}$'s (assuming zero energy spread). The trap(at V_F) transit time(π/ω_z) is an upper limit for τ since the post LEAR deceleration methods preserve ΔE and thus τ. For the kinetic energies and trap size considered $\tau \geq$ 100ns, much longer than easily feasible transient times for switching $\Delta V \leq$ 20Kv. The entire cycle may be repeated on the electron cooling time electron cyclotron radiation time scale ($\leq \frac{1}{2}$ sec).

Criteria for the transient trap filling are: (1)maximal τ; (2)minimum perterbation of the cold cloud; (3) and minimum V_0 for a fixed desired $N_{max}e$. (1)and(3) imply z_0 large. (2) forces the choice of a symmetrical (about trap center) potential step. Larger τ is possible with differential endcap potentials during injection but this would expel the lighter electrons on a time scale $\ll \tau$. Criteria (3) forces the endcap to be negative relative to the (grounded) ring. This allows only an infinitesimal potential step, $\Delta V = V_0 - V_F$ to capture injected monochromatic beam.

In reality $\Delta V \geq \Delta E_{beam}$, and $\tau \leq \pi/\omega_z$. Figure 2 shows the exact relationship between $\Delta V/\Delta E$ and τ expressed as a fraction of the empty trap axial period ($2\pi/\omega_z$) this makes clear the need for the very lowest possible LEAR emittances. IBS and space charge (Lasslett) limit 5 Mev LEAR phase space volume, even with e^- cooling, to $\Delta p/p \times \varepsilon_V \times \varepsilon_H \approx 10^{-3}\times4\pi\times3\pi$ μm^2. Thus $\Delta E \sim 2.5$Kv, which will require (fig. 2) a step $\Delta V \approx$ 8Kv for a $z_0 \approx$ 10cm trap to capture τ =100ns (1/27 of LEAR @ 5Mev). This total

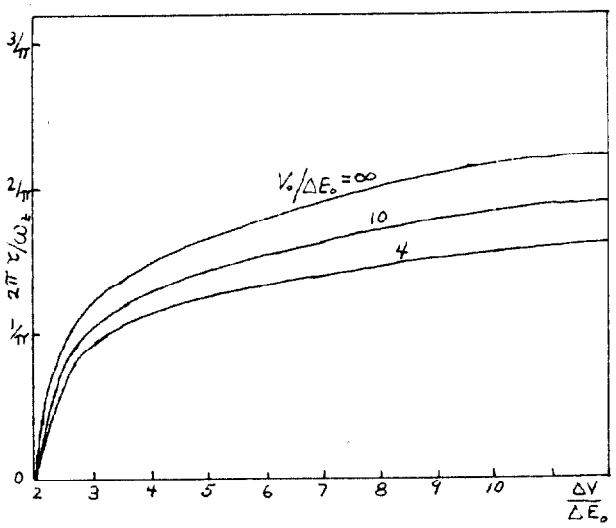

Fig. 2 τ in units of empty trap axial period for trap voltages scaled in terms of p beam spreaad, ΔE_0
$E_0 - V = \Delta E$.

trap potential, V≈ 28Kv could be reduced by further pre trap deceleration, for instance by an electrostatic "drift tube" arrangement. However peak trapped N_{max} would be less due to instabilities, and $\bar{p}$ beam transport would be very difficult. Accumulating space charge pushes $V_F(t)$ up, however it decreases ΔV for a given τ. Optimization of the accumulation requires a programmed $V_F(t)$ and $V_o(t)$ to follow track $e N(t)$.

The large (≥50 πmm) 20 Kev emittances require full focusing transport up to the trap endcap to achieve a small injection spot size (≤2mm ϕ). The RFQ must be distant for vacuum isolation (≥meter). Note that even at 7Tesla $\bar{p}$ trajectories through the fringe field are not adiabadic (λ_c≈40cm). However proper placement of the final focus just upstream of the endcap can take advantage of the deceleration to ≤3Kv from where essentially "frozen on field lines" transport (cyclotron radius <.1mm) takes over. Fortunately an all electrostatic transport system is possible.

The above trap parameters allow 4×10^{11} p to be trapped if we remain a factor 4 below the limit, Eqn 3. With 50% transfer efficiency this will require 400 accumulation cycles from LEAR initially filled with 2×10^9 $\bar{p}$. The extreme requirements on LEAR beam phase space density and on post RFQ $\bar{p}$ transport could be considerably relieved by accumulating stochastically extracting τ length "peels". In direct proportion to benefit, this requires more cycles to reach a given N, which in fact means lower equilibrium N_{max} since parasitic losses associated with trap cycling/injection will practically determine N_{max}.

Suppose $N_{max}=10^{11}$-10^{12} $\bar{p}$ are stored (together with ~10^7 e^-) in such a way that N_{max} is limited only by such parasitic losses. What is the storage half life, t_{st}? Vacuum may certainly dominate. However vacuua better than 10^{-10}Torr are expected since the trap can be sealed off after accumulation(in fact a simple "shutter"after the RFQ will probably be required). Besides this, one worries about "analogous" diffusion radially of the cloud edge. Although forbidden by exact L_z conservation, various mechanisms, e.g. trap shape imperfections, break the azimuthal symmetry.[3] Experiments with electrons at densities 4×10^{-4} the Brioullin limit show anomolous diffusion $z_0^{-1}\, dp/dt \leq 10^{-4}$/s, whence $N_{max}\approx10^{12}$ in the trap of table 1 have space sufficient for filling to 5×10^{-3} the Brioullin limit density. The anomolous diffusion is believed due to electromagnetic couplings($\propto e/m$) to the azimuthal imperfections, implying much lower rates for $\bar{p}$ clouds.

Several other, plasma instability related, anomolous cloud growth mechanisms have been investigated. Two stream instabilites associated with the trapped e^- (which have ω_m much different from $\bar{p}$) are expected[11] but are avoided since the e^- can easily be ejected from the trap.[2] To make up for any residual anomolous effects there exist experimentally proven (with e^- and $\bar{p}$) magnetron cooling techniques.[2] In principle such cooling should work even at the high densities considered here although an auxillary electron cloud may be required.

Optimized Trap

Capacity of the QUAD trap can be scaled up in proportion to z_0^3 by the prescription $V_o \propto z^2$. This maintains any given Brioullin condition (Eqn. 3) and allows for constant density ($n_p \propto N_{max}/Vol \sim V_o z_o/z_o^3 \sim z_o^3/z_o^3$). However it is likely that the V_o≈ 28Kv trap is close to the practical V_o limit. Therefore, the fixed Vo scaling of N_{max} is very unfavorable compared with a cylindrically elongated trap. Such traps have been used in dense e^- cloud studies.[3] If the cylinder radius is $\sqrt{2}z_o$ and its length L, N_{max} is $(L/z_o)^2$ times that possible for a $\rho_o=\sqrt{2}z_o$ QUAD trap. Further, the number trappable from LEAR per cycle is ~L/z_o times larger (for fixed V_o). Several of the sharply resonant cloud cooling techniques are no longer as efficient in this geometry, but for the space charge of interest this may be a slight advantage for the QUAD trap.

Ultimately superconducting solenoid volume is the practical limiting factor. Approximately ½m^3 of 6-7Tesla could contain $10^{13}$$\bar{p}$ which could still be considered a "portable" magnet.

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