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 (or for studies at low (table top) energies is well documented. 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 abuliae by a different group of collaborators, aimed at precision studies of clouds of, or single \( \bar{p}, p, \) or ions in large storage time traps. Second, there is work, experimental and theoretical, from the plasma physics tradition aimed at characterizing non neutral plasmas.

The Quadrupole Penning Trap

The highest precision studies to date on \( e^+ \) and protons have been conducted in Penning traps (electrostatic axial confinement, magnetic radial confinement, overall cylindrical symmetry) with quadrupolar electrostatic fields. 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 \( p, \bar{p}, n \) sources being internal) providing immeasurably high vacuum. Electrons are stored for indefinite periods ( \( \sim \) year observed) with no perturbation. This is a crucial point for \( \bar{p} \) storage since the \( \bar{p} \) capture on background gas cross section is divergent in the limit \( T \to 0 \). For instance, \( P \approx 10^{-14} \text{Torr} \) 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 Be window which doubles as the end window of a \( A = 2 \) \bar{p} Penning trap. This in way up to \( \sim 100 \) of \( \bar{p} \)'s should be trapped. Note that single protons have been detected, cooled and manipulated in similar traps.

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

Instead, initial \( \bar{p} \) temperatures of \( \geq 2 \) Kev will be electron cooled. An internally generated, cold, electron cloud is easy to maintain at trap center. Calculation predicts initial damping rates \( \times 10^4 \) for 3 Kev \( \bar{p} \)'s moving through \( \rho_c = 10 \text{ cm}^{-2} \) (easily achieved in practice).

\[ V_+(p_z) = V_0 (z^2 - p^2/2)/2_{0} \]

In this section I restrict discussion to \( \bar{p} \) capacity of the Penning trap itself. The highest stored \( \bar{p} \) numbers, \( N_{\text{max}} \), will require cyclic accumulation in an \( \text{open} \) (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 \( (\rho_0 = 2 \rho_d) \),

\[ V_+(p_z) = V_0 (z^2 - p^2/2)/2_{0} \]  

For the parameter values of the Penning trap, \( \Omega_c \leq 0.1 \text{ mm} \), which is initially preserved by the strong trap field, \( \Omega_c < 0.2 \text{ mm} \). 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" for the electrons this canonical momentum and hence the cloud radius can be externally manipulated at will ("magnetron cooling"). For the \( \bar{p} \)'s a natural ellipsoidal equilibrium cloud shape is arrived at. For densities \( 10^7 \text{ p/cm}^3 \) this cloud has well defined edges (falling of in \( \lambda_c \), \( \leq 0.1 \text{ mm} \)) inside of which the density is constant. 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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REMOTE ANTIPROTON SOURCES

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TABLE 1: HIGH CAPACITY \( \Phi \) BOTTLE PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z_0 )</td>
<td>10 cm</td>
</tr>
<tr>
<td>( p_b )</td>
<td>14.1 cm</td>
</tr>
<tr>
<td>( V_0 )</td>
<td>28 kV</td>
</tr>
<tr>
<td>( V_f (\Delta V = V_0 - V_f) )</td>
<td>25 kV</td>
</tr>
<tr>
<td>( \tau )</td>
<td>100 ns</td>
</tr>
<tr>
<td>B (solenoidal)</td>
<td>7 T</td>
</tr>
<tr>
<td>( r_s ) (cyclotron radius ( b ))</td>
<td>( 0.68 \mu m )</td>
</tr>
<tr>
<td>( r_s ) (cyclotron radius ( \theta ))</td>
<td>80 ( \mu m )</td>
</tr>
<tr>
<td>( N_{\text{max}} ) (( \alpha V_0 p_0 ))</td>
<td>( \times 10^{12} )</td>
</tr>
<tr>
<td>( n_{\text{max}} )</td>
<td>( \times 10^{10} ) cm(^{-3} )</td>
</tr>
<tr>
<td>Brioullin Limit (( b ))</td>
<td>( 1.3 \times 10^{11} ) cm(^{-3} )</td>
</tr>
<tr>
<td>( T ) (cold cloud temp.)</td>
<td>( &lt; 5 ) K</td>
</tr>
<tr>
<td>( j_0 ) (Debye length, ( n_{\text{max}} / T ))</td>
<td>3.2 ( \mu m )</td>
</tr>
<tr>
<td>( \omega_{\text{plasma}} n_{\text{max}} \theta ) max ( \omega_{\text{plasm}} )</td>
<td>( 4.8 \times 10^8 ) rad/s</td>
</tr>
<tr>
<td>( \omega / 2\pi (\Delta p) )</td>
<td>1.9 GHz</td>
</tr>
<tr>
<td>( E_0 (\Phi \text{ energy into trap}) )</td>
<td>20 keV</td>
</tr>
</tbody>
</table>

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

\[ V_{\text{sc}}(p, z) = 4\pi \alpha (\Delta p z^2 + \Delta z^2) \]

where \( \Delta p \) + \( \Delta z \) = 1. Equilibrium demands \( \frac{\partial}{\partial z} (V_{\text{sc}}(0, z) + V_0(0, z)) = 0 \). This condition plus \( N_{\text{tot}} = n_A 4\pi \) \( \Phi \) (2 \( \Phi \) in terms of \( G \) and \( n_0 \). Note that the potential contour eccentricity does not exactly (approx. however) correspond to the ellipsoid eccentricity. Demanding a spherical distribution gives the characteristic constraint:

\[ a/z_0 = (\Delta p_{\text{tot}}/V_0 z_0) \frac{1}{2} < 1 \]

(2)

which is the condition that the axial potential well be destroyed by space charge. \( V_0 = 20 \) kV and \( z_0 = 10 \) cm gives this ideal limit of \( 2 \times 10^{12} \) \( \Phi \). However \( a/z_0 \rightarrow 1 \) 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 cyclotum accumulation the lower, transient, \( V_{\text{trap}} \) associated with \( \Phi \) injection (next section) ought to be regarded as the limit for accumulation.

The criteria for radial trapping sets the Brioullin limit for magnetic field strength.

\[ \Delta p^2 < 3 \left[ \frac{e}{(\Phi/mc)^2} - \frac{1}{2} eV_0 / z_0^2 \right] = \frac{3}{2} \left[ 4n^2 - \omega_z^2 \right] \]

(3)

The magnetic term dominates for table 1 values. For \( V_0 = 1 \) kV, \( z_0 = 1 \) cm, one has \( \Delta p < 1.5 \times 10^{10} \) cm\(^2\). Such fields necessitate superconducting magnets, which have long been required in single particle precision work for different reasons.

Accumulation Procedure

Fast extracted bunches from LEAR can be decelerated to within range of electrostatic final deceleration (trapping by either an auxiliary low energy ring (ELENA\(^+\) or via RFQ). The feasibility of phase space preserving deceleration via RFQ from \( 5 \) keV to \( 20 \) kV has been checked and such a device is being developed for LEAR. Therefore I assume use of an RFQ but note that it brings with it the complications of high frequency (1000-4000 MHz) pre-bunching (e.g., in LEAR) post debunching, and relatively poor pre-trap vacuum (2 \times 10\(^{-10}\) Torr).

The general accumulation scheme is as follows. A length \( \Phi \) bunch is fast extracted from LEAR. This bunch is decelerated to \( E = 20 \) keV in an RFQ, and proceeds via direct vacuum path through a small \( \Phi \) (2 mm \( \Phi \)) 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 \( V_{\text{esc}} \) (existing cold cloud) then \( V_f \) must be increased by \( 20 \) keV-\( V_{\text{esc}} \). In order to stop the \( \Phi \)\( s \) (assuming zero energy spread). The trap (\( V_f \)) transit time \( (\omega_x, \omega_y) \) is an upper limit for \( \tau \) since the post LEAR deceleration methods preserve \( \Delta E \) and thus \( \tau \). For the kinetic energies and trap size considered \( \tau > 100 \) ms, much longer than easily feasible transient times for switching \( \Delta V \approx 20 \) kV. The entire cycle may be repeated on the electron cooling time electron cyclotron radiation time scale (\( \tau \) sec).

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

In reality \( \Delta V > \Delta E_{\text{beam}} \) and \( \leq \tau n / \omega \). Figure 2 shows the exact relationship between \( \Delta V / \Delta E \) and \( \tau \) expressed as a fraction of the empty trap axial period \( (2\pi / \omega) \). This makes clear the need for the very lowest possible LEAR emittances. In practice, high emittance \( \Phi \)s can achieve the limit 5 MeV LEAR phase space volume, even with \( \omega \) cooling, to \( \Delta E_{\text{beam}} \approx 10^{-4} \) MeV cm\(^2\) (Lasslett). Thus \( \Delta E_{\text{beam}} \approx 2.5 \) kV, which will require (fig. 2) a step \( \Delta V \approx 8 \) kV for \( z_0 \approx 10 \) cm trap to capture \( \tau = 100 \) ms (1/27 of LEAR 9 5 MeV). This total
trap potential, \( V \approx 28 \text{KV} \) could be reduced by further pre-trap deceleration, for instance by an electrostatic "drift tube" arrangement. However peak trapped \( N_{\text{max}} \) would be less due to instabilities, and \( \vec{p} \) beam transport would be very difficult. Accumulating space charge pushes \( V_{t}(t) \) up, however it decreases \( \Delta V \) for a given \( t \). Optimization of the accumulation requires a programmed \( V_{p}(t) \) and \( V_{o}(t) \) to follow track \( \alpha N(t) \).

The large (\( \leq 25 \text{um} \)) 20 KeV emittances require full focusing transport up to the trap endcap to achieve a small injection spot size (\( \leq 2 \text{mm} \)). The RFQ must be distant for vacuum isolation (\( 2 \text{m} \)). However proper placement of the final focus just before the endcap can take advantage of the deceleration to \( \leq 3 \text{KV} \) from where essentially "frozen on field lines" transport (cyclotron radius \( \leq \text{1mm} \)) takes over. Fortunately an all electrostatic transport system is possible.

The above trap parameters allow \( 4 \times 10^{11} \vec{p} \) 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 \( 2 \times 10^{9} \vec{p} \). The extreme requirements on LEAR beam phase space density and on post RFQ \( \vec{p} \) transport can be considerably relieved by accumulating stochastically extracting \( \pi \) length "peels". To obtain this direct proportion to benefit, this requires more cycles to reach a given \( N \), which in fact means lower equilibrium \( N_{\text{max}} \) since parasitic losses associated with trap cycling/injection will practically determine \( N_{\text{max}} \).

Ultimately superconducting solenoid volume is the practical limiting factor. Approximately \( \text{1m}^{3} \) of \( 7 \text{Tesla} \) could contain \( 10^{12} \vec{p} \) which could still be considered a "portable" magnet.

References

11. R.C. Davidson, Non Neutral Plasmas.

Optimized Trap

Capacity of the QUAD trap can be scaled up in proportion to \( z_{p} \) by the prescription \( V \sim z_{p} \). This maintains any given Brionulli condition (Eqn 3) and allows for constant density \( n_{e} N_{\text{max}}/V_{q}(t) \sim V_{s2}/z_{p} \sim z_{p}/z_{20} \). However it is likely that the \( V \approx 28 \text{KV} \) trap is close to the practical \( V_{s2} \) limit Therefore, the fixed \( V_{s} \) scaling of \( N_{\text{max}} \) is very unfavorable compared with a cylindrically elongated trap. Such traps have been used in dense \( \vec{e} \) cloud studies. If the cylinder radius \( z_{c} \) and its length \( L \), \( N_{\text{max}} \) is \( (L/z_{20})^{2} \) times that possible for a \( p_{c} = z_{20} \) QUAD trap. Further, the number trappeable from LEAR per cycle is \( \sim L/z_{20} \) times larger (for fixed \( V_{s} \)). 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.