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# Test system for trapping and resistively cooling $H^+$ to cryogenic temperatures *

Steven L. Cornford and R.A. Kenefick
*Physics Department, Texas A&M University, College Station, Texas, USA*

A 4 K Penning trap is described which is suitable for demonstration of resistive cooling of protons or antiprotons in the LANL antigravity experiment. High circuit $Q$'s (600-20000) are achieved and normal-mode trap resonances are driven and detected in the process of optimizing system performance. Most recent results are discussed.

## 1. Introduction

Large numbers of antiprotons cooled by LEAR (CERN) to 2 MeV and subsequently pre-cooled to ~ 100 eV must be brought to lower velocity in order to measure their gravitational acceleration by the Earth [1]. A sufficient number of $\bar{p}$'s near an end-point speed of 5 m/s will be available if ~ $10^5$ $\bar{p}$'s per extraction are in a thermal distribution with an average energy of ~ 10 K. Passive ("resistive") cooling [2] is a well-understood method which can be extended to achieve such a velocity distribution. Ions in a Penning trap induce currents [3] in the trap electrodes and dissipation of these induced currents in the parallel resistance of a tuned circuit will cool the ions [2,4]. The rate of cooling is greatly enhanced by matching the natural resonant frequencies and widths (i.e. the $Q$) of the electrode structure to that of the ions. The cooling time constant is given by $\tau_c = \kappa m d^2/q^2 R$, where $m$ is the ion mass, $q$ is the ion charge, $d$ is the characteristic dimension of the motion being cooled, $R$ is the parallel resistance of the tuned circuit ($R = Q/\omega_0 C$), and $\kappa$ is a geometrical factor less than but near 1 [4]. In a viable small trap, the time constant for cooling the cyclotron motion can be reduced to ~ 1 s, which couples fairly rapidly to the axial motion through ion-ion scatering. The eight cooling time constants required to reach 10 K from 100 eV are then sufficiently brief to retain all of the trapped $\bar{p}$'s in a good ultrahigh vacuum. At liquid helium temperature (4.2 K) this level of vacuum is routinely obtained [5] and has been practically demonstrated in the trapping and storage of $\bar{p}$'s in another experiment [6].

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## 2. Method

Beam optics constraints [7] suggested that the transverse coordinate (and consequently the accessible transverse mode, $f_+$) should be cooled so a ratio $r_0/z_0 = 0.4$ is used [8]. This enhances cyclotron image currents and is quite different from the usual value of $\sqrt{2}$ but does not affect the trapping characteristics. A circuit $Q$ of ~ 1000 would reduce $\tau_c$ to less than 1 s, but collective effects might degrade the rate at the lowest temperatures [9].

Although techniques exist for achieving system temperatures below 4 K these were judged not to be justified until cooling to ~ 10 K had been demonstrated by a less elaborate technique. A recent experiment [6] using a "compensated" cylindrical Penning trap has measured the charge-to-inertial mass ratio of the $\bar{p}$ and constitutes a successful demonstration of an alternative cooling method using collisions with radiation-cooled electrons.

## 3. Apparatus

The inductor used in the resonant circuit (see fig. 1) is a rather specific design which we have named a Zeroth Order Toroid (or ZOT). It is a very high $Q$ inductor compatible with UHV baking and has excellent heat conduction properties at 4 K. Bare NbTi wire of $\frac{1}{7}$ mm diameter is wound on uniformly grooved synthetic sapphire tubes and two such straight solenoids are placed side-by-side with opposing axial fields for first order far field cancellation. Cancelling the far field in this way reduces $Q$ spoiling couplings to neighboring conductors. Measured $Q$'s for this NbTi ZOT are ~ 8000 when resonated with the trap, although $Q$'s of ~ 20000 have been obtained by resonating with a silvered mica capacitor. Measured dc contact resistances