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Cylindrical Penning Traps and Self-Shielding Superconducting Solenoids for High Precision Experiments

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Abstract

The antiproton and proton inertial masses have been measured to be the same to a fractional accuracy of 4×10^{-8} by our TRAP collaboration at CERN. Two key experimental advances were employed which have a wider applicability for mass spectroscopy. A high-precision cylindrical trap with open-endcap electrodes allows free access to the trap center for particle loading, and a self-shielding superconducting solenoids system cancels fluctuations in the ambient magnetic fields.

1. Cylindrical Penning trap

A Penning trap is an important tool for studies of single elementary particles, high resolution mass spectroscopy of elementary particles and ions, and for precision tests of fundamental physics. The trap employs a strong magnetic field to radially confine charged particles, and an electric field to keep the charged particles from escaping along the magnetic field lines. If particle containment is the only goal, neither the specific shape of the electrodes to apply the electric field (nor the homogeneity or the stability of the magnetic field discussed in Section 2) is especially important, except that a good rotational symmetry around the magnetic field axis is required for long containment times [1]. For precision experiments, however, it is generally important to closely approximate to an ideal Penning trap by using a pure electrostatic quadrupole potential and a spatially uniform magnetic field which is stable in time. Often, in fact, the trap and the trapped particles are treated as a bound system. Examples include precision measurements of the magnetic moments of the electron and the positron [2], the proton-to-electron mass ratio [3] and studies of relativistic electron motion at millielectronvolt energies [4], and precise comparisons of ion masses [5, 6].

The trap electrodes used in the mentioned experiments were painstakingly constructed along hyperboloids of revolution (Fig. 1a) because this geometry most nearly produces a quadrupole electric potential at the center of the trap. Such a potential will allow particles to oscillate along the magnetic field axis between the trap endcaps with a frequency insensitive to the oscillation amplitude. There are nonetheless significant deviations from the electric quadrupole because of unavoidable misalignments and imperfections in trap electrodes. High precision measurements of the oscillation frequencies can be attained when such anharmonicities are tuned out by introducing an extra set of compensation electrodes and adjusting their potential [7, 8] (Fig. 1b). Theoretical studies [9, 10] of the electrostatics of this process showed that with an appropriate geometry, the trapping well depth can be made independent of anharmonicity tuning, to make an "orthogonalized" Penning trap. They also suggested that the need for hyperbolic electrodes may not be as strong as had been assumed leading to consideration of a cylindrical trap geometry as an alternative [11].

Cylindrical Penning traps have two important advantages over hyperbolic traps. First, cylindrical electrodes can be machined to a higher accuracy in less time. Second, it is easier to study theoretically the anharmonicity compensation since the electrostatic potentials can be calculated analytically. An orthogonalized cylindrical Penning trap with flat endcaps (Fig. 2a) has been used to obtain equally good signal-to-noise ratio, demonstrating its suitability for high precision experiments [12] (Fig. 2b). The trap has also been shown to be a good approximation to an ideal cylindrical microwave cavity where the cavity radiation field can

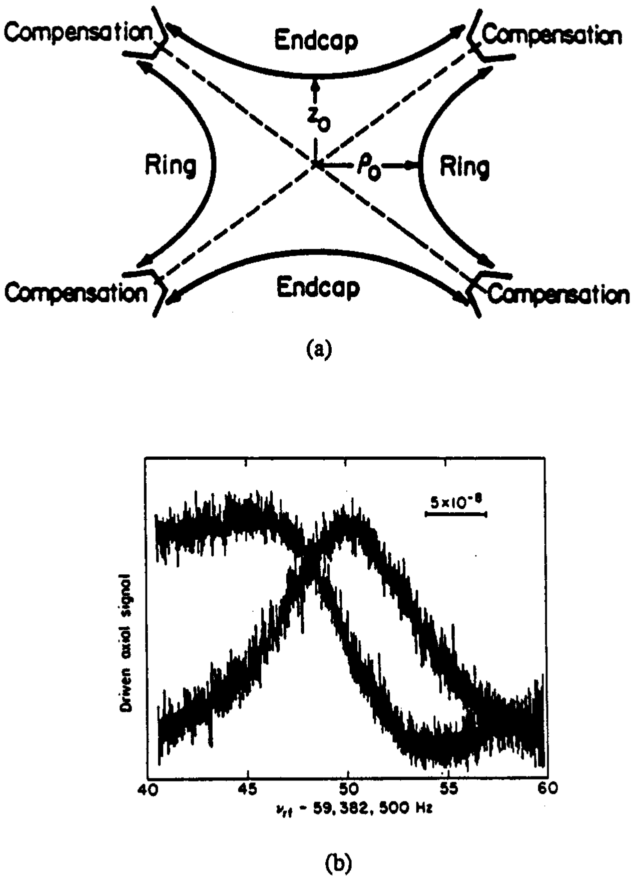
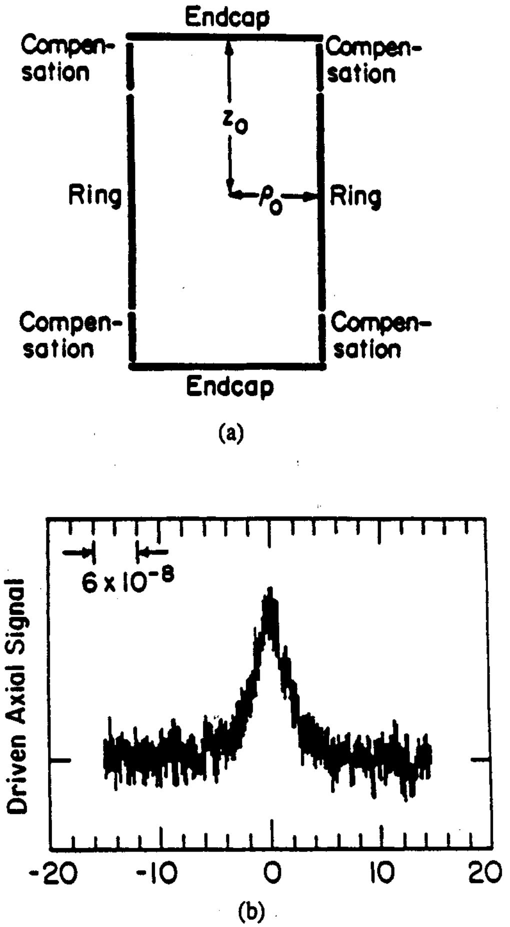


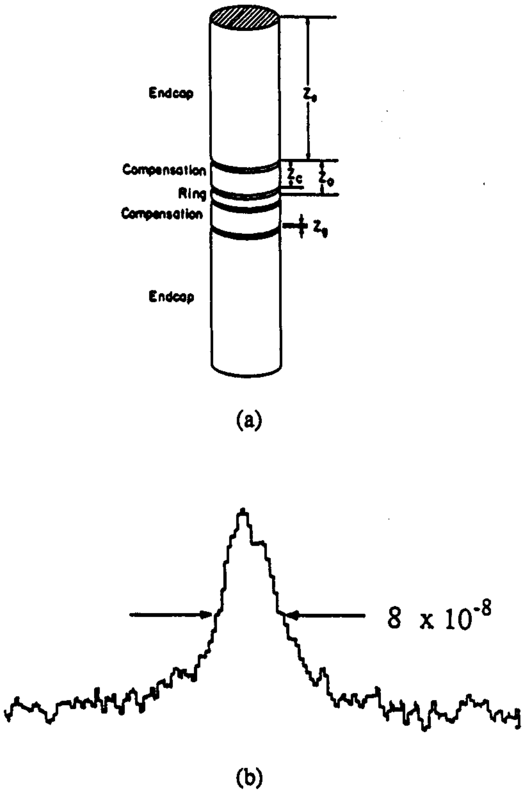
Fig. 1. Hyperbolic Penning trap with compensation electrodes (a) and narrow axial coherent resonances of a single electron observed in the hyperbolic trap (b) (Ref. [8])



(a)

(b)

Fig. 2. Orthogonalized cylindrical trap with flat endcaps (a) and narrow driven axial resonance of one electron therein (b) (Ref. [12])



(a)

(b)

Fig. 3. Open-endcap cylindrical trap (a) and narrow axial resonance of driven electrons (b) (Ref. [16])

be probed with trapped electrons, opening the way to a new generation of electron magnetic moment measurements, not limited by either cavity frequency shifts or damping widths, and to sideband cooling of an electron motion to millikelvin temperatures [13].

Another type of Penning trap with cylindrical geometry is a cylindrical trap with long, open-ended endcap electrodes [14] (Fig. 3a). The great advantage of this electrode configuration is the open access to the interior of the trap, which makes it easy to load particles such as antiprotons from LEAR (Low Energy Antiproton Ring at CERN) and to introduce microwaves and laser beams. The harmonicity and the orthogonality of the trapping potential well near the trap center can be simultaneously achieved by inspecting the analytic expressions of the electric potentials which are derived in detail in Ref. [14]. An optimized trap configuration is also chosen, which is suitable for high precision work such as our recent measurement of the antiproton inertial mass [15]. Very narrow resonances due to coherently driven axial motion of a few electrons are obtained in this trap [16] (Fig. 3b), which is currently being used by our TRAP (TRapped AntiProton) collaboration at CERN. Such traps can be used not only for high precision mass measurements of antiprotons, but also for cooling of trapped antiprotons [17], and possibly for producing antihydrogen [18].

2. Self-shielding superconducting solenoids

In ion cyclotron resonance (ICR) and nuclear magnetic resonance (NMR) experiments, the cyclotron frequencies of ions and the precession frequencies of nuclear spins in a strong magnetic field are precisely measured and compared to the frequencies of other species in the same strong field. Since these frequencies are proportional to the magnetic field, the accuracy is compromised when the magnetic field changes during measurement times, for example, due to fluctuations of the ambient magnetic field. Although high-frequency components in the fluctuating ambient field are shielded by eddy currents induced in various cylindrical conductors surrounding the trap, low-frequency components generally cause significant changes in the magnetic field and the measured frequencies. Subways, nearby elevators and cars pulling into nearby parking lots often produce the largest variations in the ambient field. Typical ambient magnetic field has been measured in our laboratory at Harvard with a fluxgate magnetometer [19, 20]. During a few hours at night, when the nearby subway stops running, the fluctuations are of order 0.1 mG with occasional steps of order 0.6 mG. During daytime, on the other hand, much larger fluctuations up to 3 mG are typically observed. The situation becomes even worse in the hostile environment of an accelerator laboratory. For example, the proton synchrotron (PS) at CERN, which is 19 meters away from our ICR experiment in a Penning trap, perturbs the ambient field at our location up to 60 mG every few seconds [20]. Therefore it is quite crucial to shield our experimental region in high field (60 kG) from these magnetic field fluctuations, otherwise our measurement accuracy would have been limited only to 1×10^{-6} level, and 4×10^{-8} accuracy [15] achieved for the mass equality of antiprotons and protons would not have been possible. Our scheme to shield out the deadly ambient fluctuations will be summarized below.

Unfortunately, the familiar techniques to shield low-field regions with highly permeable materials like iron and μ metal do not work in high-field regions since they saturate at high fields and provide no shielding when saturated. Type I superconducting materials like lead and niobium cannot be used for effective shields of high-field region because the large field is above the critical field for these materials. A type II superconductor has been used to shield external fluctuations from a very small high-field region [21], but there was trouble with flux jumps associated with the shield. Finally, we note that two concentric, coplanar superconducting loops were used [22] to shield the high-field region by choosing the radii of the loops to minimize the magnetic field shift at the center of the loops. External field fluctuations were expected to cancel by perhaps a factor of 10. This configuration is, however, not in general useful because a field gradient is inevitably introduced and therefore the spatial homogeneity of the magnetic field would be compromized.

In the alternate approach to the required shielding, which is crucial for the high accuracy measurements, a self-shielding superconducting solenoid system [23] was devised. It consists of an extra superconducting coil added to a standard, high-field solenoid, and utilizes flux conservation to passively shield an interior volume from changes in the ambient field. Following theoretical design principles presented in Ref. [23], an additional superconducting coil, with its ends connected, was incorporated (Fig. 4) into a commercial NMR solenoid system which produces a highly homogeneous 60 kG field. Magnetic fluctuations in the central volume where experiments are located were then measured for the first time [20] to be smaller than the ambient field fluctuations by a large factor of 156 (Fig. 5) and the high degree of spatial homogeneity within the NMR solenoid was not compromised. Moreover, since the shielding is entirely passive, the system requires no adjustment or electronics for maintenance.

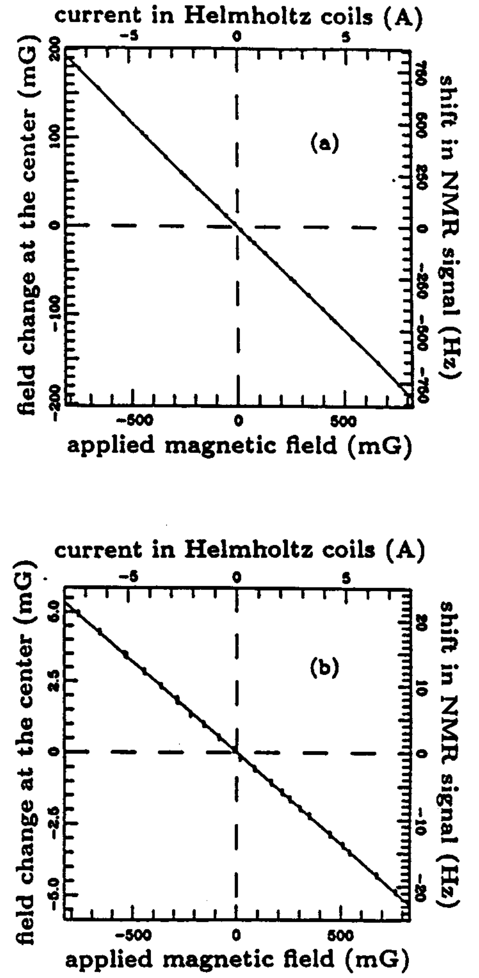


Fig. 5. Change in the magnetic field measured within the solenoid (deduced from the change in NMR frequency of an acetone sample) as a function of the external magnetic field applied over the solenoid without (a) and with (d) the added inner solenoid (Ref. [20])

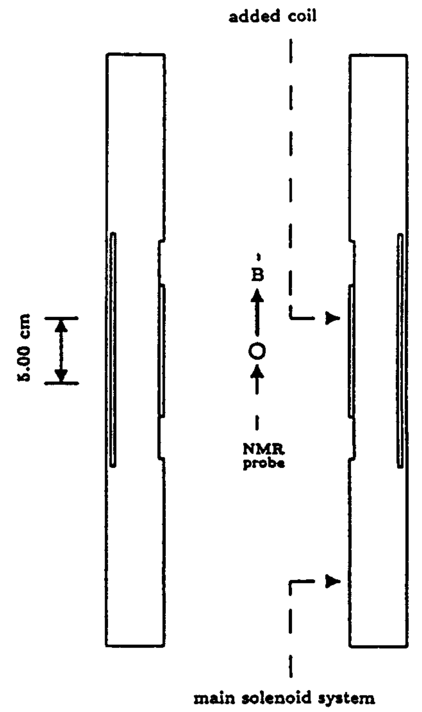


Fig. 4. Cross-section of the windings of the high-field solenoid which produces a vertical magnetic field. The innermost solenoid was added to make the solenoid system self-shield external fluctuations (Ref. [20])

This self-shielding system is essential for our ongoing antiproton cyclotron resonance experiments at LEAR, and should be useful for other applications where high field and high stability are required simultaneously and even for less precise experiments since good shielding makes it possible to make measurements much nearer to sources of fluctuating magnetic fields. Finally, we note that significant shielding can always be realized with modest additions to existing high-field solenoid systems, if the additions are made correctly [23]. In the future, even larger shielding factors may be achieved by adding small coils to the outside of a superconducting solenoid system, since these could be adjusted during solenoid construction to optimize the shielding.

Acknowledgements

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References

1. Malmberg, J. H. and O'Neil, T. M., Phys. Rev. Lett. 39, 1333 (1977).
2. Van Dyck, Jr., R. S., Schwinberg, P. B. and Dehmelt, H. G., Phys. Rev. Lett. 59, 26 (1987).

3. Van Dyck, Jr., R. S., Moore, F. L., Farnham, D. L. and Schwinberg, P. B., Int. J. Mass Spectrom. Ion Processes **66**, 327 (1985).
4. Gabrielse, G., Dehmelt, H. G. and Kells, W., Phys. Rev. Lett. **54**, 537 (1985).
5. Moore, F. L., Farnham, D. L., Schwinberg, P. B. and Van Dyck, Jr., R. S., Nucl. Instrum. Methods **B43**, 425 (1989).
6. Cornell, E. A., Weisskoff, R. M., Boyce, K. R., Flanagan, Jr., R. W., Lafyatis, G. P. and Pritchard, D. E., Phys. Rev. Lett. **63**, 1674 (1989); ibid., **64**, 2099 (1990).
7. Van Dyck, Jr., R. S., Wineland, D. J., Ekstrom, P. A. and Dehmelt, H. G., Appl. Phys. Lett. **28**, 446 (1976).
8. Van Dyck, Jr., R. S., Schwinberg, P. B. and Dehmelt, H. G., in "New Frontiers in High Energy Physics" (Edited by B. Kursunoglu, A. Perlmutter and L. Scott) (Plenum, New York 1978).
9. Gabrielse, G., Phys. Rev., **A27**, 2277 (1983).
10. Gabrielse, G., Phys Rev. **A29**, 462 (1984).
11. Gabrielse, G. and Mackintosh, F. C., Int. J. Mass Spectrom. Ion Processes **57**, 1 (1984).
12. Tan, J. and Gabrielse, G., Appl. Phys. Lett. **55**, 2144 (1989).
13. Tan, J. and Gabrielse, G., to be published in Phys. Rev. Lett. (1992).
14. Gabrielse, G., Haarsma, L. and Rolston, S. L., Int. J. Mass Spectrom. Ion Processes **88**, 319 (1989).
15. Gabrielse, G., Fei, X., Orozco, L. A., Tjoelker, R. L., Haas, J., Kalinowsky, H., Trainor, T. A., and Kells, W., Phys. Rev. Lett. **65**, 1317 (1990).
16. Jhe, W., Phillips, D., Gröbner, J. and Gabrielse, G., unpublished (1991).
17. Gabrielse, G., Fei, X., Orozco, L. A., Tjoelker, R. L., Haas, J., Kalinowsky, H., Trainor, T. A. and Kells, W., Phys. Rev. Lett. **63**, 1360 (1989).
18. Gabrielse, G., Haarsma, L., Rolston, S. L. and Kells, W., Phys. Lett. **A129**, 38 (1988).
19. Gabrielse, G., Phys. Rev. Lett. **64**, 2098 (1990).
20. Gabrielse, G., Tan, J., Clateman, P., Orozco, L. A., Rolston, S. L., Tseng, C. H. and Tjoelker, R. L., J. Mag. Resonance **91**, 564 (1991).
21. Dutta, A. and Archie, C. N., Rev. Sci. Instrum. **58**, 628 (1987).
22. Van Dyck, Jr., R. S., Moore, F. L., Farnham, D. L. and Schwinberg, P. B., Rev. Sci. Instrum. **57**, 593 (1986).
23. Gabrielse, G. and Tan, J., J. Appl. Phys. **63**, 5143 (1988).