From: Proc. 4th Symposium on Freq. Standards and Metrology, Ancona, Italy, Sept. 1988; A. Demarchi, ed. (Springer Verlag, Heidelberg).

Frequency Standards Utilizing Penning Traps*

J.J. Bollinger, S.L. Gilbert, Wayne M. Itano, and D.J. Wineland
Time and Frequency Div., National Institute of Standards and Technology
Boulder, CO 80303

1. Introduction

Ion traps have a number of characteristics that make them attractive candidates for frequency standards [1]. Ion confinement times from a few hours to a few days permit long interrogation times and therefore narrow linewidths and large line Q's. In addition, ion traps typically do not suffer from the usual perturbations associated with confinement. For example, collisions of hydrogen atoms with the confining walls of a hydrogen maser can produce fractional frequency shifts greater than 1×10^{-11} on the masing transition [2]. Stark shifts due to the confining electrostatic field of a Penning trap can, in many cases, be made less than 1×10^{-15} [3,4].

The largest systematic shift and uncertainty in a frequency standard using many stored ions is typically the second order Doppler (time dilation) frequency shift $\Delta\nu_{D2}$. For a clock transition of frequency ν_0, $\Delta\nu_{D2}$ is given by

$$\langle \Delta\nu_{D2}/\nu_0 \rangle = - \langle \vec{v}^2 \rangle / (2c^2) \qquad (1)$$

where c is the speed of light, $\vec{v}$ is the ion velocity, and < > denotes an average over the ions in the trap. Without a means of achieving low ion temperatures, this shift can be unacceptably large. For example, a 300 K $^9Be^+$ ion has a second order Doppler shift of -4.6×10^{-12}. Laser cooling [5,6] can be used to reduce the ion temperature to much less than 1 K. For Be^+ ions, this results in second order Doppler shifts smaller than -1.5×10^{-14}. In our laboratory, up to 10^5 Be^+ ions stored in a Penning trap have been laser cooled to temperatures less than 1 K. The Penning trap is therefore a suitable candidate for a laboratory microwave frequency standard where the Dicke confinement criterion [7] is easily satisfied and where it is desirable to store many ions in a trap in order to obtain a signal-to-noise ratio that gives a useful fractional frequency stability. The number of ions used in a Penning trap frequency standard is determined from a tradeoff of signal-to-noise considerations and the second order Doppler frequency shift due to the $\vec{E}\times\vec{B}$ rotation of the ions[3,8]. We note that in an rf (Paul) trap the number of ions that can be laser cooled has been typically small (< 50) due to the problem of rf heating[9].

At the previous (Third) Symposium on Frequency Standards and Metrology, the results of an initial experiment done at the National Bureau of Standards (NBS) on $^{25}Mg^+$ ions stored in a Penning trap were reported[10]. In this experiment a 12 mHz linewidth on a 292 MHz magnetic field-independent hyperfine transition in the ground state of $^{25}Mg^+$ was obtained[11]. Below we summarize the Penning trap frequency metrology work done in our laboratory since the previous symposium. In the next section the results of a frequency standard based on up to 2000 laser cooled $^9Be^+$ ions stored in a Penning trap are discussed. The inaccuracy of this frequency standard was on the order of 1×10^{-13}[4]. It was limited by the second order Doppler shift of the ions due to the ion heating during the clock interrogation period when the cooling laser was turned off. The final section of this paper discusses our current work using sympathetic cooling[12] to maintain a cold Be^+ cloud and obtain a 0.9 mHz linewidth on the Be^+ clock transition. With sympathetic cooling we project an order of magnitude improvement in the Be^+ frequency standard. In addition to the work done at NBS discussed here, frequency metrology work with ions stored in Penning traps is being conducted by groups at Orsay, France[13] and Teddington, England[14].

2. Laser-Cooled $^9Be^+$ Frequency Standard

The Penning trap uses a uniform magnetic field to confine ions in a direction perpendicular to the magnetic field. The ions are prevented from leaving the trap along the magnetic field direction by a static electric field, typically provided by three hyperbolic electrodes[1]. Figure 1 shows the hyperfine structure of the ground state of $^9Be^+$ as a function of magnetic field. At a magnetic field of 0.8194 T the hyperfine transition ν_1 (see Fig. 1) depends only quadratically on the magnetic field deviation ΔB according to $\Delta\nu_1/\nu_1 = -0.017(\Delta B/B)^2$. In spite of its relatively low 303 MHz transition frequency, ν_1 provides the basis for a frequency standard. (We have chosen to work with Be^+, because it is easy to trap and laser cool. Heavier ions such as Hg^+ offer large microwave transition frequencies but are technically much harder to work with.) A narrow-band radiation source (power $\cong$ 20-60 μW) tuned to the low frequency side of the 2s $^2S_{\frac{1}{2}}(m_I = -3/2,\ m_J = -1/2) \rightarrow$ 2p $^2P_{3/2}(-3/2,\ -3/2)$ (λ = 313 nm) transition of $^9Be^+$ was used to cool and spatially compress the ions and optically pump them into the (-3/2, -1/2) ground state[11,15]. The resonance fluorescence induced by this cooling laser was used to detect the ions. The size, density, and temperature of the ion clouds were determined by use of a similar radiation source as a probe[15]. Typical clouds ranged from a few hundred to 2000 ions with cloud diameters from 300 to 500 μm and densities of about 3×10^7 ions/cm^3. Cyclotron and axial temperatures of less than 100 mK and a second order Doppler shift due to the cloud rotation of less than 3×10^{-14} were obtained with the cooling laser applied continuously.

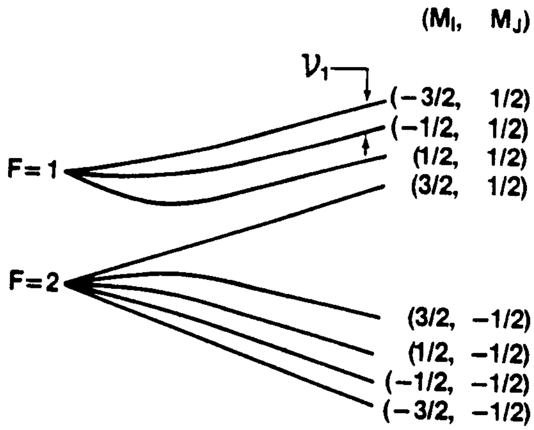

Figure 1. Hyperfine structure (not drawn to scale) of the $^9Be^+$ 2s $^2S_{\frac{1}{2}}$ ground state as a function of magnetic field. ν_1 is independent of magnetic field to first order at B = 0.8194 T.

The ν_1 transition was detected by optical-microwave-rf triple resonance. Microwave radiation tuned to the electron spin-flip resonance transferred half of the ion population from the optically pumped (-3/2, -1/2) state to the (-3/2, +1/2) state. Some of the (-3/2, +1/2) state population was transferred to the (-1/2, +1/2) state by application of rf near the 303 MHz ν_1 transition frequency. As a result of the microwave mixing this resulted in an additional decrease in the (-3/2, -1/2) state population and therefore a decrease in the observed fluorescence. The cooling laser and mixing microwaves were typically on for a period of 3 s, during which the $^9Be^+$ ions were prepared in the (-3/2, -1/2) and (-3/2, +1/2) states. The cooling laser and mixing microwaves were then turned off in order to avoid light and ac Zeeman shifts during the ν_1 interrogation period. Ramsey's method of separated oscillatory fields was used to interrogate ν_1. Typically an rf pulse of duration t = 0.5 s was applied, followed by a free precession interval of duration T = 19 s and a second rf pulse of duration t = 0.5 s coherent with the first pulse. After the interrogation period, the laser and microwaves were turned back on, and the signal was obtained from the absence of fluorescence during the first 0.3 s of this time interval. The (t,T) = (0.5 s, 19 s) interrogation resulted in a linewidth $\Delta\nu_1$ = 25 mHz and a $Q \equiv \nu_1/\Delta\nu_1$ of 1.2×10^{10} on the 303 MHz ν_1 transition frequency.

A synthesized rf source was locked to the ν_1 transition. A description of the servosystem is given in reference [4]. With about 1000 ions in the trap, a fractional frequency stability of $\sigma_y(\tau) \cong 2\times10^{-11}\tau^{-\frac{1}{2}}$ for measurement time τ in seconds was obtained with the (0.5 s, 19 s) Ramsey interrogation. The systematic uncertainty of 1×10^{-13} was dominated by the second order Doppler frequency shift [4]. During the 20 s interrogation period when the cooling laser was turned off, the ion temperature increased from less than 1 K to 35 K. This heating produced a second order Doppler shift of 4×10^{-13} on the ν_1 transition and was measured with about 25% uncertainty. The rapid heating that occurred during the interrogation period was probably caused by asymmetry-induced transport [16]. With the cooling laser off, axial asymmetries of the trap can increase the total canonical angular momentum of the ions, resulting in an increase in the ion cloud radius. As the ion cloud expands, electrostatic potential energy of the ions due to the space-charge and trap electric fields is converted into thermal energy of the ions.

3. Sympathetic Cooling

An improvement in Be^+ frequency standard performance requires a reduction in the observed heating. This can possibly be done by improvement of the trap axial symmetry. With this in mind we have constructed a Penning trap with care taken to minimize axial asymmetries. Rather than the usual hyperbolic electrodes, the trap was constructed with hollow cylindrical electrodes [17]. In addition, in order to avoid asymmetric contact potentials due to plating of the trap electrodes from the Be^+ oven when ions were loaded into the trap, a second trap, mounted below the experimental trap, was used to load the ions. The ions were then transferred to the clean experimental trap. The expansion of the Be^+ ion cloud in the cylindrical Penning trap was less than in the previous Be^+ Penning trap. However, the expansion was eliminated by using a second ion species to sympathetically cool and compress [12] the Be^+ ions. Specifically, $^{26}Mg^+$ ions were loaded into the same trap with the $^9Be^+$ ions. The Mg^+ ions were continuously laser-cooled and spatially compressed by a 280 nm (power ≅ 50-80 μW) radiation source. Through the Coulomb interaction with the Mg^+ ions, the Be^+ ions were then cooled and compressed. Due to the ion cloud rotation, the Mg^+ ions were observed to centrifugally separate and form a doughnut surrounding the Be^+ ions.

The 313 nm source was used to optically pump and detect the Be^+ ground state. It had only a small effect on the Be^+ ion temperature and cloud size and, as in the previous experiment, was turned off during the Ramsey interrogation period. Because the 280 nm Mg^+ cooling laser beam is nonresonant with any Be^+ transitions, it was left on continuously during the Ramsey interrogation period without seriously perturbing the ν_1 transition frequency. In this way a cold, steady state cloud of Be^+ ions was obtained independently of the 313 nm radiation source, which permitted the use of very long interrogation times.

In the previous triple resonance experiment (optical-microwave-rf) only half of the stored Be^+ ions were used to measure the ν_1 transition due to the microwave mixing. The stable field of the superconducting magnet used in the present experiment permitted the following quadruple resonance procedure which used all of the stored ions to measure the ν_1 transition. The Be^+ ions were optically pumped into the (3/2, 1/2) ground state by tuning the 313 nm source to the 2s $^2S_{\frac{1}{2}}(3/2,1/2) \rightarrow$ 2p $^2P_{3/2}(3/2,3/2)$ transition. The 313 nm source was turned off and the ions were transferred to the (1/2,1/2) and then the (-1/2,1/2) state by successive 0.2 s Rabi π pulses. After Ramsey's method of separated oscillatory fields was used to interrogate ν_1, the ions remaining in the (-1/2,1/2) state were transferred back to the (3/2,1/2) state by reversing the order of the previous two Rabi π pulses. The 313 nm source was turned back on, and the signal was obtained from the absence of the Be^+ fluorescence during the first few seconds after the 313 nm source was turned on. In addition to increasing the number of ions used to measure the ν_1 transition, this procedure increased the signal by a factor of 4. The long (-3/2, +1/2) $\rightarrow$ (3/2, 1/2) laser repumping time also allowed the signal counting time after the 313 nm source was turned back on to be increased. This increased the signal-to-noise ratio by increasing the change in the number of detected photons for each ion that made the clock transition.

With sympathetic cooling, long interrogation times were possible. Figure 2 shows the signal obtained with a (1 s, 550 s) Ramsey interrogation. The 0.9 mHz linewidth gives $Q = 3.3\times10^{11}$ on the ν_1 clock transition. If used to servo a local oscillator, this linewidth along with the estimated signal-to-noise ratio should result in a fractional frequency stability of $\sigma_y(\tau) = 3.8\times10^{-12}\tau^{-\frac{1}{2}}$ ($\tau > 1100$ s). This stability is consistent with the stability of our reference oscillator and is about a factor of 8 or 9 larger than the stability estimate based on the number of stored ions [8]. Shorter (1 s, 5 s) Ramsey interrogations resulted in a signal-to-noise ratio within a factor of 2 of the estimate based on the number of stored ions.

Preliminary estimates of all known systematic uncertainties for the transition frequency of Fig. 2 are less than 1×10^{-14}. With the use of an imaging tube, the cloud rotation frequency and radial distribution of the Be^+ ions were determined. The second order Doppler shift due to the cloud rotation was calculated to be -4×10^{-15}. From previous observations, we believe the sympathetic cooling provided Be^+ temperatures « 1 K and second order Doppler shifts less than 1×10^{-14}. The ac Stark shift due to the 280 nm source is estimated to be less than 1×10^{-15}. Due to the rotation of the earth, there is a systematic shift of $2.46(0.05)\times10^{-14}$ [4]. All other known systematic shifts are estimated to be less than 1×10^{-15}.

In the future we plan to evaluate the use of sympathetically cooled Be^+ ions to steer a local oscillator. With a passive hydrogen maser [2] as a source for the local oscillator, we may be able to obtain a fractional frequency stability of $\sigma_y(\tau) = 2\times10^{-12}\tau^{-\frac{1}{2}}$ ($\tau > 1000$ s), limited by the stability of the passive hydrogen maser. An inaccuracy of less than 1×10^{-14}, limited by the second order Doppler shift, appears feasible.

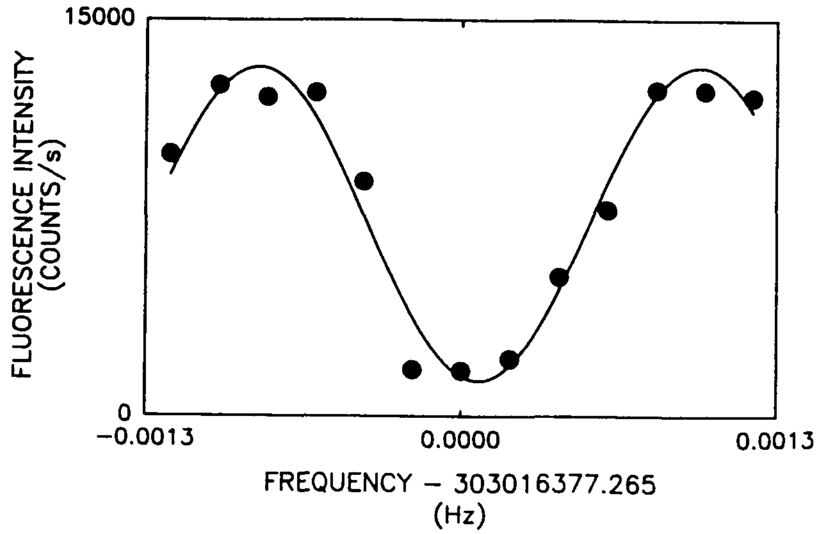

Figure 2. Signal obtained with 3200 Be^+ ions on the ν_1 field independent transition with a 550 s Ramsey free precession period. The data are the result of one sweep. The sweep width is 2.4 mHz and the frequency interval between points is 0.2 mHz. The dots are experimental and the curve is a least squares fit. A signal-to-noise ratio of 12 is estimated from the fit.

We gratefully acknowledge the support of the U.S. Air Force Office of Scientific Research and the U.S. Office of Naval Research. We thank C. Weimer and D. Heinzen for carefully reading the manuscript.

References

1. See for example D.J. Wineland, W.M. Itano, and R.S. Van Dyck, Jr.: Adv. At. Mol. Phys. 19, 135 (1983) and references therein
2. F.L. Walls: Proc. of the IEEE 74, 142 (1986)
3. D.J. Wineland, W.M. Itano, J.C. Bergquist, and F.L. Walls: in Proc. of 35th Ann. Freq. Control Symposium (USAERADCOM, Ft. Monmouth, NJ 07703) p. 602 (1981); D.J. Wineland in Precision Measurement and Fundamental Constants II, ed. by B.N. Taylor and W.D. Phillips (Natl. Bur. Stands. (U.S) Spec. Publ. 617, 1984), p. 83
4. J.J. Bollinger, J.D. Prestage, W.M Itano, and D.J. Wineland: Phys. Rev. Lett. 54, 1000 (1985)
5. S. Stenholm: Rev. Mod. Phys. 58, 699 (1986)
6. D.J. Wineland and W.M Itano: Physics Today 40, 34 (June 1987)
7. R.H. Dicke: Phys. Rev. 89, 472 (1953)
8. D.J. Wineland et al.: these proceedings

9. D.A. Church and H.G. Dehmelt: J. Appl. Phys. 40, 3421 (1969)
10. D.J. Wineland, J.C. Bergquist, R.E. Drullinger, H. Hemmati, W.M. Itano, and F.L. Walls: J. Phys. (Paris) Colloq. 42, C8-307 (1981)
11. W.M. Itano and D.J. Wineland: Phys. Rev. A24, 1364 (1981)
12. D.J. Larson, J.C. Bergquist, J.J. Bollinger, W.M. Itano, and D.J. Wineland: Phys. Rev. Lett. 57 70 (1986)
13. F. Plumelle, M. Desaintfuscien, M. Jardino, and P. Petit: Appl. Phys. B41, 183 (1986)
14. R.C. Thompson, G.P. Barwood, and P. Gill: Appl. Phys. B46, 87 (1988)
15. L.R. Brewer, J.D. Prestage, J.J. Bollinger, W.M. Itano, D.J. Larson, and D.J. Wineland: Phys. Rev. A38, 859 (1988)
16. C.F. Driscoll, K.S. Fine, and J.H. Malmberg: Phys. Fluids 29, 2015 (1986)
17. S.L. Gilbert, J.J. Bollinger, and D.J. Wineland: Phys. Rev. Lett. 60, 2022 (1988)