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Letter to the Editor

Long-Term Behaviour of Cavity Phase Difference in NBS-6 *

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Abstract

A critical review of all beam-reversal phase-shift measurements carried out on NBS-6 (NBS-5) since 1973 is presented. The analysis takes into account a recent study of frequency shifts in atomic-beam frequency standards resulting from overlapping tails of adjacent lines. A strongly correlated variation of the cavity phase difference with time is shown, which appears to fit nicely on an exponential decay curve with a time constant of 3.7 years. The suggestion is made that some mechanical relaxation in the microwave structure may be responsible for this phenomenon. Furthermore, the line-pulling model seems to suggest a better explanation for observations previously attributed to distributed cavity phase shift. Verification of these interpretations through more involved evaluations may allow substantial reductions in the error budget for the standard.

Introduction

A recent analysis of Rabi pulling [1] and a beam-reversal accuracy evaluation on NBS-6 including this effect [2] have spurred the present review of past evaluations; where indicated, adjustments are made on retrievable data to take into account this newly revisited systematic effect. Improved understanding is gained of long-term variations of end-to-end cavity phase difference as well as effects previously attributed to distributed cavity phase shift.

Twelve measurements of the cavity phase shift by methods including beam reversal have been carried out since NBS-5 was first operated in early 1973. Except for 1974, when magnetic trimmers were inserted to prevent Majorana transitions in the interfaces between selecting magnets and C-field region, and modifications were made at the tube ends to improve beam reversibility (whereby the standard was renamed NBS-6), a complete accuracy evaluation has been carried out every year.

The procedure followed to determine the end-to-end cavity phase difference was in all cases well documented in the laboratory notebooks, as were all the precautions taken to guarantee reproducibility of beam optics; it is clear that great care was taken in always reproducing oven, detector and beam-stops positioning. This is fortunate because, while all other effects were properly accounted for in all evaluations, to the extent of spending efforts in lengthy velocity-distribution measurements for the calculation of the second-order Doppler shift, Rabi pulling was not always adequately addressed. The latter is strongly dependent on beam optics, and if this was closely reproduced at all times it is possible to introduce today first-order corrections today on past measurements, based on the data shown in [2] for the C-field dependence of Rabi pulling. Data from the 1984 analysis of Rabi pulling [2] is presented as a function of C-field in Fig. 1.

Distributed Cavity Phase Shift

Measurements of signal level, output frequency and Ramsey linewidth as a function of detector position were made in 1976 [3]. At that time, the observed change in output frequency with detector position was attributed to distributed cavity phase shift. This apparent sensitivity to distributed cavity phase shift has led to the dominant term in the error budget for NBS-6 and has been responsible for the care taken in subsequent evaluations to insure accurate repositioning of the oven and detectors to ± 0.3 mm.

The slope of the Rabi-pulling curve for the magnetic field value used in the 1976 analysis ($f_z=$

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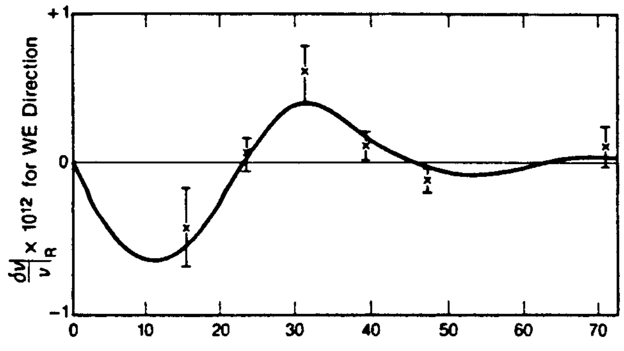

Fig. 1. Fractional frequency shifts induced by Rabi pulling as a function of C-field strength. The field strength is represented in units of frequency differency, f_z, between the clock transition and the first field-dependent transition. The experimental points are from Ref. [2] and the solid curve is derived from Ref. [1] with a scaling factor to best fit the data

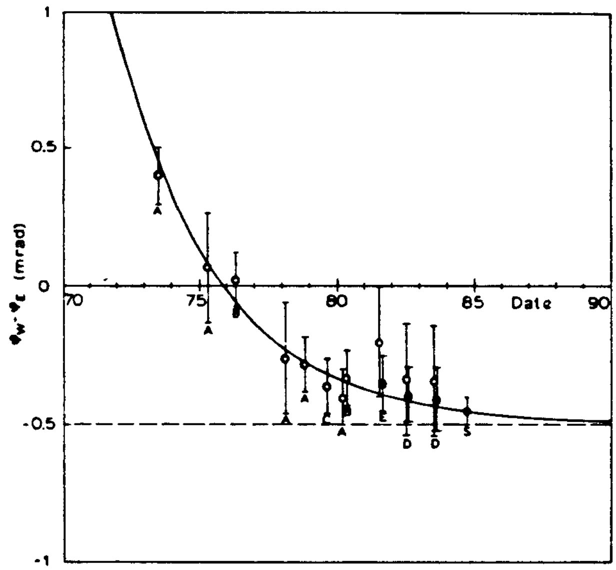

Fig. 2. Phase-difference measurements as a function of time for the NBS-6 cavity. The Zeeman frequency for the different points was as follows: A) 42–43 kHz; B) 23–24 kHz; C) 40 kHz; D) 50 kHz; E) WE: 43 kHz, EW: 47 kHz; S) Sweep of various C-field values

23 kHz) is about $+1 \times 10^{-13}$/kHz at optimum power (Fig. 1). In light of the new model and data for Rabi pulling, a reinterpretation of the 1976 data now seems plausible.

The Ramsey linewidth was observed to vary together with the output frequency when the detector position was changed. This variation in linewidth must correspond to a difference in mean beam velocity; a conclusion that is supported by virtue of the fact that the direction of detector motion is in the plane in which the atomic beam is dispersed by the dipole magnetic-state selectors. A change in beam velocity has, in turn, the effect of rescaling the Rabi-pulling curve (Fig. 1) by a corresponding fraction. With this model then, the observed variation in output frequency with detector position can be accounted for by Rabi pulling. In fact, it turns out that both sign and magnitude of the frequency shifts observed in Ref. [3] can be predicted with the Rabi-pulling results of Ref. [2] together with the linewidth changes observed in Ref. [3]. This model can be further verified by subsequent measurements of output frequency as a function of detector position with different C-field values. For example, at a C-field corresponding to $f_z = 38$ kHz, an effect of approximately half the size and opposite in sign should be observed as compared to the 1976 measurements. Unfortunately, this test of the model will have to wait until a rebuilding of NBS-6 is completed. However, should the model be confirmed, the errors attributed to distributed cavity phase shift can be substantially reduced. Since these errors have dominated the NBS-6 error budget [3], it may, in the future, be possible to tighten the accuracy limits on this standard.

End-to-End Cavity Phase Shift

The difference between cavity phases at West end and East end ($\Phi_W - \Phi_E$) as calculated from measurements of beam-reversal frequency difference at optimum power (for NBS-6) is plotted for the various evaluations in Fig. 2 as a function of time. Error bars are attributed according to the extensiveness of performed system checks and calculations. Different Zeeman frequencies, f_z, and different approaches were used and the apparatus underwent many beam reversals. Various scientists were involved in these experiments over more than a decade and their efforts should all be acknowledged. It seems highly unlikely that the human factor or a systematic pattern in C-field values or in preferential Cs deposition on one cavity end may account for the observed long-time correlation of these measurements. A review of the various points follows with attention given to clues for correction of Rabi pulling.

The 1973 evaluation of NBS-5 (Glaze, Hellwig) involved an extrapolation to zero microwave power [5] in which case the Rabi-pulling contribution vanishes [1, 2]. The first two points for NBS-6 (Wineland [3]) were stated after finding experimentally (at least in one beam direction) low deviations from the quadratic field-dependence of frequency and concluding that Rabi pulling was smaller than 0.5×10^{-13}. It is clear today after the more complete C-field sweep of Ref. [2] that only by good fortune did the two f_z values used for those measurements happen to be near two zero crossings of Rabi pulling. The following two measurements (Garvey, Hellwig) did not include a similar check of the pulling but were taken near a zero crossing and therefore need no correction. The same holds for point C of 1979 (Stein) and the two points of 1980 (Lewis [6]). However, for the latter two a direct evaluation of the pulling was made by measuring the difference in slope at the two sides of the central Rabi line. It was concluded that the effect was very small ($\ll 10^{-13}$). This check was not carried out for the two following points of 1981 and 1982 (Lewis [7]) which were taken at different C-field values. In particular, the 1981 point was calculated from measurements at two different C-field values for the two directions[1] and it appears from Ref. [2] that a correction of more than 1×10^{-13} should be introduced as shown in Fig. 2 (black point). A smaller error bar has been given to this corrected point to show that Rabi pulling has been taken into account. The 1983 point (Wineland, Bergquist) was taken, like the preceding one, at $f_z = 50$ kHz and a small correction (-10^{-13}) in the same direction of point E is suggested by Ref. [2] to account for Rabi pulling. This would bring these two points very near the indicated solid curve (black points). This set of (corrected) points fits nicely on an exponential curve whose parameters are calculated with a least-squares optimization. A time constant of 3.7 years, an initial value of $+9\times10^{-4}$ radians (Jan. 1972) and an asymptotic value of -5×10^{-4} radians yield a root-mean-square deviation from the curve of 3×10^{-5} radians for the phase differnce. This corresponds to a root-mean-square frequency deviation of 3×10^{-14}. The latter is most likely due to residual unaccounted – for Rabi pulling and/or possibly to distributed phase shift. The total variation of the end-to-end cavity phase difference has been about 10^{-3} radians over the life of the cavity; this corresponds to a variation of the difference in electrical length of the two arms equivalent to about 100 μm [8]. It seems reasonable to assume that some kind of mechanical relaxation may have taken place in the cavity structure (which is built of copper) producing a decreasing exponential change in the length difference of the arms of this order of magnitude. Chemical phenomena on the cavity surface seem a less likely cause because of the long time constant of the observed process.

Conclusions

The error budget for NBS-6 has been dominated by a conservative estimate of possible distributed cavity phase shift. However, these errors can be substantially reduced once further measurements of frequency shift vs. beam optics confirm the model proposed here. The assumption has been made in this paper that the beam optics have been reproduced over the years and that the proposed model for Rabi pulling is correct. The fact that the data produced in this way fit on a smooth, plausible curve tends to support the validity of the assumptions.

The following conclusions can now be drawn: *1)* The beam optics have not changed significantly over the years and today's results on Rabi pulling can be used to correct past measurements[2]. *2)* The sensitivity of the standard to beam optics depends on the Zeeman frequency. For example, variations with detector positioning a factor of 2 smaller than and of opposite sign from those observed in [3] would be expected at $f_z = 38$ kHz. *3)* The uncertainties due to distributed cavity phase shift in NBS-6 are smaller than previously thought.

Modifications to NBS-6 are presently under way involving rebuilding the electronics and improvement of the oven and detector chambers so that more frequent and more precise changes in position can be made. These modifications should allow the more elaborate evaluations in which Rabi pulling is explicitly addressed as a function of oven and detector position.

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[1] This fact can be taken as an indication of the little importance which was given to Rabi pulling at the time

[2] The only evaluation for which this point cannot be applied is the one carried out on NBS-5 before the 1974 modifications [4]. However, as pointed out above, the method used in that evaluation avoided Rabi pulling