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Mapping the magnetic field vector in a fountain clock

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We show how the mapping of the magnetic field vector components can be achieved in a fountain clock by measuring the Larmor transition frequency in atoms that are used as a spatial probe. We control two vector components of the magnetic field and apply audio frequency magnetic pulses to localize and measure the field vector through Zeeman spectroscopy.

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Keywords: fountain, magnetic field

I. INTRODUCTION

The changes in the atomic energy levels induced by a magnetic field can have a strong effect on the experimental results and the accurate mapping of the magnetic field in an experimental apparatus is often essential in improving the precision of the measurement. The very high sensitivity of atoms to magnetic field can be utilized to provide the measurement of the field, as implemented in atomic vapor magnetometers^{1,2}. Here the Zeeman splitting of the atomic energy levels in the presence of the magnetic field is measured through absorption spectroscopy with a probe field.

In experimental schemes where the location of atoms can be controlled, e.g. atomic

fountain clocks, the atoms can serve as a spatial probe of the scalar magnetic field³, thus, building a map of the magnetic field distribution in the experimental apparatus.

When the magnetization of atoms has to be controlled, the information on the magnetic field orientation becomes important. It is common to apply controlled bias magnetic fields along different polarization directions in order to measure the vector components of the magnetic field under test⁴.

We show how to achieve the localized measurement of the magnetic field vector. We build a map of the magnetic field vector components by controlling the bias magnetic fields along two polarization directions and by controlling the location of atoms in the experimental apparatus and their interaction time with the probe field. As a probe, we use

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a pulsed magnetic field, oscillating at Larmor frequency. The Larmor absorption spectrum measures the Zeeman energy levels shift and, therefore, the magnetic field. We discuss different physical effects that can influence the accuracy of the measurement. This method can be used with atomic fountain or thermal beam clocks with arbitrary operating magnetic field orientation, where the bias magnetic fields along two polarization directions can be applied. We present the experimental method as applied in NRC-FCs1 fountain clock and analyze the uncertainties of this measurement.

In primary frequency standards, the accurate mapping of the magnetic field is essential for the determination of frequency corrections and uncertainties^{5,6}. Despite the best design efforts, due to the geometry of the standard and the environmental changes, a nonuniform and temporally varying magnetic field is usually produced and needs to be evaluated. In atomic fountain clocks for accuracy requirements at the level of one part in 10^{16} and better, the information on both the magnitude and the direction of the magnetic C-field is needed. We will now describe how the measurement is done under the operating conditions of the fountain: in high vacuum, at the operational magnetic field settings and with a low density atomic cloud acting as the magnetic field sensor that has a benign effect

on the field distribution.

In an atomic fountain, shown schematically in Fig. 1 for NRC FCs1, the atoms are first cooled in magneto-optical trap, MOT, and then launched up in the $\hat{z}$ direction. The atomic cloud twice passes the microwave Ramsey cavity: on the way up and on the way down. In the cavity the transition between two hyper-fine levels of the ground state is excited. The evolution of the atomic wave-function in the drift region between the two Ramsey excitations provides the basis for the clock frequency measurements. The atoms launched in the fountain travel in the magnetic C-field, $\mathbf{B}_C$, that shifts the hyper-fine Zeeman energy sub-levels, m_F , and, as a result, the accumulated phase of the atomic wave-function. The phase change, although small for only the quadratic Zeeman shift of $m_F = 0$ sub-levels, translates into the systematic clock frequency shift and its uncertainty depends on the accuracy of the magnetic field measurement along the drift region. The best resolution in $\mathbf{B}_C(z)$ is desired.

The Zeeman energy splitting and, therefore, the magnitude of the C-field, B_C , can be probed directly in the operating fountain by interrogating the atoms in $m_F \neq 0$ sub-levels that exhibit a linear shift proportional to the magnitude of the magnetic field. By carefully controlling the interaction time of atoms with the C-field and with the interro-

gating field, the vertical map of $B_C(z)$ can be reconstructed. In the past different methods using microwave, MW³, and audio frequency, AF⁷, magnetic field pulses were used. Both methods provided localized measurement of B_C along the launch axis, thus building a map of $B_C(z)$.

We show now how to extend the measurement of the magnetic field in the fountain to access not just the absolute, but the vectorial value of $\mathbf{B}_C(z)$. In order to measure the $\mathbf{B}_C$ vector components, (B_x, B_y, B_z) , we apply a controlled magnetic field along two directions in the fountain. The values for all B_i components are then derived from the following equations (1).

$$\begin{aligned} B_C &= \sqrt{\sum_i B_i^2}, \\ B_i &= B_{i,0} + B_{i,V}, \quad i = x, y, z. \end{aligned} \quad (1)$$

The $(\hat{x}, \hat{y}, \hat{z})$ is the orthogonal basis and is chosen according to the geometry of the rods and the launch axis in the fountain respectively. The magnetic field $B_{i,0}$ represents the vector i component of the C-field in the operating state of the fountain and $B_{i,V}$ is the experimentally controlled part used for field mapping purposes only. Only two $B_{i,V}$ need to be varied experimentally and their effect on B_C measured to permit all three $B_{i,0}$ to be derived through fitting to equation (1).

One way of constructing the vector-map of $\mathbf{B}_C$ is by measuring the Ramsey resonance shift of magnetically sensitive $\Delta F =$

$1, \Delta m_F = 0, m_F \neq 0$ and $\Delta F = 1, \Delta m_F = \pm 1$ transitions as a function of the C-field vector components parallel and perpendicular to the microwave field. We use a different method and probe with the Larmor excitation $\Delta F = 0, \Delta m_F = \pm 1$ transitions. The Ramsey cavity provides a π microwave pulse that transfers the population between $F_{3,0} \leftrightarrow F_{4,0}$ levels⁸. A short AF magnetic pulse, Larmor field, aligned perpendicular to the C-field, is applied on the atomic cloud while in apogee, z_A , exciting $\Delta F = 0, \Delta m_F = 1$ transitions. The final measurement detects population changes in $F_{3,0}, F_{4,0}$ levels as a function of the AF frequency.

The magnitude of $B_C(z_A)$ is derived from the Larmor resonance frequency defined by the Zeeman shift of $m_F \neq 0$ levels. The measurement is repeated for different settings of $B_{x,V}$ and $B_{y,V}$ at each launch height z . The necessary number of measurement points at each z for a good estimate on $B_{i,0}$ depends on the number of free parameters in the model and the signal to noise level of the experiment.

In the general case where the magnetic field strength is controlled by the current in rods or coils, the change in current in one set of conductors may affect all three vector components of the field as shown in equation (2):

$$\mathbf{B}_V = \mathbf{I} \cdot \mathbf{K}_{ij}, \quad (2)$$

where the $\mathbf{K}_{ij}$ matrix measures the conversion coefficient, k_{ij} , of current, $\mathbf{I}$, component I_i to magnetic field along $\hat{j}$, $B_{j,V}$. In addition, the k_{ij} components may vary with location $\mathbf{r}$ and in cases where this effect is strong it results in the broadening of the Zeeman energy levels and the measured Larmor resonance. In order to account for these and other effects, the model would require a greater number of free parameters and the accuracy of the fit would degrade. It is preferred to use the least number of variables when possible. We use a rod structure that allows a simple model. For example, we operate in the regime where the magnetic field B_V changes linearly with the applied current; we use a small step size of down to 1 cm along the launch axis and we use the 10 mm diameter aperture of the shutters, one located below the state selection cavity and another below the Ramsey cavity^{9,10}, to improve the transverse resolution.

II. MEASUREMENTS

The design of FCs1¹⁰ includes a rectangular Ramsey cavity with the microwave field aligned along $\hat{y}$ axis and six vertical aluminum rods that run along the fountain body, $\hat{z}$ axis, and are used to generate the C-Field, as schematically shown in Fig. 1. Four C-field rods, marked C-1 to C-4, are

connected together to produce a uniform DC magnetic field in the $\hat{y}$ direction. Two more alignment or AL-field rods, AL-1 and AL-2, produce a field in the $\hat{x}$ direction with a relative uniformity estimated to be better than $8 \cdot 10^{-4}$ near $\hat{z}$ axis¹¹.

FIG. 1. Schematic view of magnetic field generating rods in NRC fountain. Four rods C-1,2,3,4 produce $\hat{y}$ direction C-field; two rods AL-1,2 produce $\hat{x}$ Alignment-field. In a typical experiment we apply DC currents on C- and AL-rods and a pulse of AF current, to excite Larmor transitions, on AL-rods only.

We use two computer controlled function generators to apply both DC and AF pulsed current on C- and AL-field rods in-

dependently. The AF pulse is timed with the launch sequence of FCs1, its magnitude and duration are controlled through the software. The Larmor resonance absorption is measured⁸. It is important to evaluate the $\mathbf{B}_C$ at the level used for operating clock. In the case of FCs1, it has been set to 1.6mG.

In NRC FCs1 fountain we can neglect off-diagonal elements of the k_{ij} matrix in equation (2). In addition, we do not apply current I_z to control $B_{z,V}$. Thus we can use the following equation (3) to construct the $\mathbf{B}_C$ map:

$$B_C = \sqrt{(B_{x,0} + k_{xx}I_x)^2 + (B_{y,0} + k_{yy}I_y)^2 + B_{z,0}^2}. \quad (3)$$

This model has five free parameters $B_{x,0}, B_{y,0}, B_{z,0}, k_{xx}$ and k_{yy} . Hence, at each z at least five different combinations of $(B_{x,V}, B_{y,V})$ have to be measured through Larmor resonance. This solution leaves an ambiguity in the sign of $B_{z,0}$ which can be resolved with a $B_{z,V}$ if desired. Generally we scan the AF pulse frequency to measure the Larmor resonance under different experimental conditions and apply Gaussian fitting to derive resonance line characteristics such as frequency, width and amplitude. One launch cycle of the fountain provides one measurement point and takes 1.25 seconds.

We use rectangular (few tens of milliseconds) current pulses to produce the AF magnetic field pulse. It is important to find the

optimum between transform limited spectral resolution, Δf , of the rectangular AF pulse and the resonance broadening due to magnetic field variation along the vertical spread, Δz , of the atomic cloud centre position during the application of the pulse. Since we interrogate atoms at the apogee, Δz is minimized. The cloud size at the apogee remains below 30 mm FWHM under all launch configurations used in the current study. The experimental results of the Larmor spectrum as a function of the AF pulse duration are shown in Fig. 2 and are summarized in the caption. We selected 60 ms AF pulses as the optimum to be used in our experiments. With the 60 ms AF pulse, the Larmor spectrum width, $\Delta\nu_L$, is not transform limited, while the vertical resolution of the measurement is ≈ 35 mm, only slightly larger than the cloud size.

There are several variables in the experiment that require evaluation and adjustment for each launch height, z , in order to conduct a consistent mapping of the magnetic field $\mathbf{B}_C(z)$. First, under normal fountain operation we measure with a $\pi/2$ Ramsey microwave pulse at 9.2 GHz, the spectrum of the $F = 3, m_F = 0 \leftrightarrow F = 4, m_F = 0$ transition to derive the launch height, z . The next steps are executed with the π pulses in the microwave cavity and the measurement is of the Rabi spectrum of the Larmor resonance.

FIG. 2. (Colour online) Markers - Larmor spectrum measured with different AF pulse durations. Solid lines - Gaussian fit. Launch height 22 cm. Legend: ΔT - AF pulse duration; $\Delta\nu_L$ - Larmor spectrum width (FWHM); Δz - distance below the apogee at times $\pm\Delta T/2$; Δf - spectral resolution of a rectangular AF pulse (FWHM). marker- $[\Delta T$ (ms), Δz (cm), $\Delta\nu_L$ (Hz), Δf (Hz)]: $\circ$ -red - [20, 0.05, 3000, 44]; $\square$ -blue [40, 0.20, 23, 22]; $\diamond$ -green - [60, 0.44, 16, 12]; ∇ -black [80, 0.78, 14, 11]; $\triangle$ -yellow [100, 1.23, 12, 9].

Second, we measure how the Larmor spectrum changes as a function of the time, T , the AF pulse is applied during the launch sequence. Resonance width, amplitude and frequency, ν_0 , change with T symmetrically around the apogee. Figure 3 summarizes the results for $\nu_0(T)$ for the launch height of 22 cm above the Ramsey cavity. The point of symmetry, shown with arrow, is used for fur-

ther measurements. A difference in ν_0 can be observed in Figure 3 between atoms being interrogated at the same height on their way up ($T \leq 375$) and on their way down ($T \geq 575$). This can be attributed to the thermal expansion of the atomic cloud during the ballistic flight.

FIG. 3. Markers - Fitted (Gaussian) resonance frequency, ν_0 , for different AF pulse application time, T . The arrow ($\uparrow$) indicates the apogee. Dashed line - parabolic fit to data points, minimum at $T = 480$. Launch height 22 cm.

Third, we optimize the AF current pulse amplitude. The penetration of the AF magnetic field inside the copper cylindrical body of the fountain depends on the AF frequency and the distance away from the ends of the drift tube. At each launch height we measure the Larmor efficiency as a function of the AF pulse amplitude to find the linear operating regime (see arrow in Figure 4), because working away from linear absorption can skew the Larmor resonance spectra, an

integrated measurement of the magnetic field distribution over the probe volume, leading to an increased error in the derived magnetic field.

When the alignment angles between $\mathbf{B}_C$ and AF and $\mathbf{B}_C$ and MW change from the optimal (90° and 0° respectively), the Larmor and the Ramsey transition efficiencies drop. During the experiment, while changing the $B_{x,V}$ and $B_{y,V}$, we change the $\mathbf{B}_C$ value and orientation, thus varying the Larmor resonance frequency and transition efficiency. By optimizing the nominal AF pulse intensity we mitigate the skewing that these changes can lead to.

FIG. 4. Larmor efficiency measured as a function of AF pulse amplitude. The arrow ($\uparrow$) points to the AF pulse amplitude for linear absorption regime. Launch height 22 cm. At AF amplitudes above 2au, the onset of Rabi oscillations is observed.

When the AF pulse frequency is scanned, the duration of the pulse, ΔT , is varied due

to the method used to generate the pulse. We compensate for this change by rescaling the AF pulse amplitude, B_{AF} , to maintain a constant product of $B_{AF} \cdot \Delta T$ and, hence, the symmetry of the Larmor absorption spectrum.

After the experimental parameters are chosen for each launch height, the measurement of $B_{x,0}$, $B_{y,0}$ and $B_{z,0}$ is done. We measure the Larmor resonance frequency for different values of current applied on C- and AL-rods, I_C and I_{AL} correspondingly. Typical results are shown in Fig. 5. It can be clearly seen by comparing pairs of curves with the same value of I_C , and two values of I_{AL} with opposite signs (e.g. 1 and 2, 4 and 5) or vice versa (e.g. 6 and 7) that the values of ν_0 are not preserved for the same $|I_C|$ or $|I_{AL}|$. This change in ν_0 arises due to the residual vector components of the magnetic field $\mathbf{B}_C$, $B_{i,0}$, that we are evaluating.

As seen in Fig. 5, the Larmor absorption magnitude decreases with higher ν_0 . This is due to a reduced penetration of the AF magnetic field inside the copper fountain body at higher frequencies. This effect, when uncompensated as in our case, increases measurement uncertainty of $\nu_0(I_C, I_{AL})$ due to a reduced signal to noise ratio and a shift away from the optimal absorption regime, identified in Fig. 4.

Using $\nu_0(I_C, I_{AL})$ values derived from mul-

FIG. 5. (Colour online) Launch height 22 cm. Larmor spectra measured (markers) with different DC magnetic field values. Solid lines - Gaussian fit. The settings for DC currents in the C-field and the AL-filed rods used to produce the total magnetic field in each case: curve # $-(I_C; I_{AL})$ [arb. units]: 1- (1.83;0.2), 2- (1.83;- 0.2), 3- (2.03;0.0), 4- (2.03;- 0.2), 5- (2.03;0.2), 6- (- 2.23;- 0.2), 7- (2.23;- 0.2), 8- (- 2.03;- 0.3)

multiple measurements over a grid of values for I_C and I_{AL} we fit equation (3), using Matlab implementation of the Nelder-Mead simplex algorithm¹², to obtain $B_{i,0}(z)$ values for FCs1 under clock operating conditions ($I_C=2.13$ au, $I_{AL}=0$ au). In Table I we present some of the fit results and the summary of the magnetic field vector mapping is also shown graphically in Fig. 6. The C-field vector has the major component in $\hat{y}$ direction as expected, however, at the height correspond-

TABLE I. The measurement results for several locations along the fountain axis for the C-Field magnitude, B_C , and vector components, $B_{i,0}$. The height, z , is the height above the Ramsey microwave cavity. These and additional values were used to build the vector map shown in Fig. 6.

z (cm)	B_C (mG)	$B_{x,0}$ (mG)	$B_{y,0}$ (mG)	$B_{z,0}$ (mG)
2.5	1.564 ± 0.003	-0.230 ± 0.003	1.55 ± 0.01	0.00 ± 0.16
4.4	1.606 ± 0.005	-0.124 ± 0.002	1.29 ± 0.00	0.94 ± 0.07
6.7	1.702 ± 0.003	-0.035 ± 0.002	1.70 ± 0.06	0.00 ± 0.45
12.3	1.715 ± 0.002	-0.030 ± 0.002	1.69 ± 0.08	0.00 ± 0.58
22.3	1.6376 ± 0.002	-0.035 ± 0.004	1.63 ± 0.00	0.10 ± 0.04
32.6	1.580 ± 0.003	-0.089 ± 0.002	1.42 ± 0.01	-0.62 ± 0.21
41.7	1.551 ± 0.002	-0.096 ± 0.003	1.35 ± 0.01	-0.70 ± 0.20

ing to the edge of the Ramsey cavity cutoff waveguides, 5 cm, an increase in $B_{x,0}$ and $B_{z,0}$ is observed. We discuss the measurement uncertainties cited in Table I and the systematic uncertainties of the method in the next section.

III. DISCUSSION

The B_C values are derived directly from the measurements of ν_0 and the uncertainty for B_C is less than $\pm 5 \mu\text{G}$, typically $< 2 \mu\text{G}$, as can be seen in Table I. This measurement uncertainty can be improved by using smaller step size in the AF pulse frequency scan, $\Delta\nu_L$, (all reported results were obtained

FIG. 6. C-Field vector map in NRC FCs1. The dominant orientation of the field is along the $\hat{y}$ -axis, but small $\hat{x}$ and $\hat{z}$ components are present at heights less than 10cm above Ramsey cavity, at the edge of its cutoff waveguides (shown in Fig.1). The B_z scale is in [mG], one division on z-axis is equivalent to 10mG. Note scale differences.

using $\Delta\nu_L \geq 1.5$ Hz).

The values of $B_{i,0}$ were derived from fitting to equation (3) and the quality of fit was evaluated using the reduced χ^2 parameter¹³. The value for χ^2 ranged between 0.7 and 1.9 for different heights, z , indicating a reasonable quality of fit for the typical number of free parameters, ν , in our experiment ($\nu = 10$ to 20). We derived the measurement uncertainties, reported in Table I from $1/\nu$ increase in χ^2 . The largest error occurs in $B_{z,0}$, since its

value was not probed directly in our experiment. The uncertainty in $B_{z,0}$ is a combined uncertainty of $B_C, B_{x,0}$ and $B_{y,0}$. Heights where the reported fit results show strong modulation in $B_{i,0}$ values are marked as warranting more measurements over a larger grid covering $(\pm I_C, \pm I_{AL})$ ranges.

We discuss next the systematic uncertainties in the measurement method. We evaluate the systematic uncertainties for our experimental conditions but one should carefully re-evaluate their importance when the specifics of the experiment change.

Several systematic uncertainties can arise from the variation of the magnetic field in the probe region. First, the Millman effect⁵ (p.805) caused by a rotation of the DC magnetic field, that can shift the Larmor resonance frequency for $\Delta m_F = \pm 1$ transitions. In our case these transitions are driven near the apogee and, therefore, pass through the varying magnetic field twice (on the way up and on the way down). This cancels the Millman frequency shift in the measurement and only resonance line broadening can occur due to imperfect cancellation and transversal spread of the atomic cloud. In our experiment, at the height where the rotation of $\mathbf{B}_C$ is the strongest, we estimate the worst case line broadening of the order of 4.5 Hz, much smaller than typical Larmor resonance FWHM of 20 Hz.

Second, we consider the Messiah adiabatic condition⁵ (p.512) for $\mathbf{B}_C$ field uniformity in magnitude and orientation. When not satisfied, it can lead to Majorana transitions⁵ (p.836) between different Zeeman sub-levels, m_F , change their population distribution and skew Larmor resonance spectrum. We evaluate the adiabatic condition ω/ν_0 and ω_1/ν_0 for $d\mathbf{B}/dt = \bar{\omega}_1\mathbf{B} + \bar{\omega} \times \mathbf{B}$ for the worst case when atoms pass through the inhomogeneity region at highest speed. In our experiment this occurs when launching to 50 cm above Ramsey cavity, while the strongest change in $\mathbf{B}_C$ is at the height of 3 cm. We find $\omega=150$ Hz and $\omega_1=5$ Hz, both $\ll 550$ Hz of the Zeeman splitting of $m_F = \pm 1$ levels at the height of 3 cm. We estimate the resulting maximum possible change in the measured population is $< 3 \times 10^{-4}$ and the resulting error in the measured magnetic field is $< 0.5 \mu\text{G}$.

Third, we consider the AC Zeeman frequency shift⁵ (p.799), due to the AF magnetic pulses, that is present through the quadratic Zeeman effect only, while the linear Zeeman shift cancels for AC fields. The quadratic Zeeman shift has the same value for all m_F of the same hyperfine level F . Our measurement probes Larmor transitions with $\Delta F = 0$ and, therefore, the AC Zeeman shift cancels in our experiment.

Fourth, we consider the fractional fre-

quency Bloch-Siegert shift⁵ (p.817) in Larmor resonance, ν_0 , due to the presence of the AF field. In our experimental setup we do not have the exact measurement of the AF magnetic field magnitude inside the fountain drift tube, but can only estimate its value from the Larmor transition efficiency curve shown in Fig.4. Here the Rabi frequency is 8.3 Hz and at the nominal operating AF pulse magnitude of 1.5 ($=0.5\pi$ pulse area, units as in Fig.4), the expected Bloch-Siegert shift is $< 0.1 \mu\text{G}$. To verify our estimate experimentally, we have measured the change in ν_0 as a function of AF current pulse magnitude. We scanned the AF pulse frequency for different values of AF magnitude ranging from 0.5 ($=0.17\pi$) to 2.5 ($=0.83\pi$). We found that the change in ν_0 was ± 0.4 Hz, which amounts to $\pm 1.1 \mu\text{G}$. This value agrees, within the resolution of the measurement, with the estimated relative shift of $\pm 0.1 \mu\text{G}$.

Fifth, the hysteresis effect that can potentially arise due to changing $B_{i,V}$ values in the process of the experiment. We have measured the Larmor resonance before and after applying DC magnetic field of 4 mG and 11 mG for 2 minutes on C- and AL-rods respectively. Within the resolution of our measurements we observed no change in ν_0 .

IV. CONCLUSION

We have developed a method for measuring magnetic field vector components in atomic fountains. The choice of the C-field dominant orientation does not affect the methodology and it can be readily applied in its current form to atomic fountains with C-field along $\hat{z}$. The technique can be easily transferred to other experiments where the applied magnetic field can be controlled along two directions and its effect probed by the subjects of the experiment like atoms, e.g. thermal beam clocks.

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