Evaluation of Magnetic Field Homogeneity using Cold Atoms as Sensors in Cesium Fountain Atomic Clock

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NPLI-CsF1 is an approved primary frequency standard indigenously developed at CSIR-National Physical Laboratory, India [1]. One of the key frequency corrections in cesium fountain frequency standards is the C-field-induced frequency shift. A small value of magnetic field known as c-field is crucial for eliminating degeneracy in magnetic sub-states of Cesium atoms during their interaction with microwaves in the flight region. The homogeneity of this magnetic field is necessary to minimize Zeeman shift and associated systematic frequency errors. However, variations in magnetic field homogeneity along the atom trajectory induce a second-order Zeeman shift, adding a frequency bias to the final fountain frequency. This necessitates precise magnetic field mapping inside the ultra-high vacuum (UHV) during fountain evaluation, performed repeatedly at regular intervals. This paper discusses the method, using ultra-cold cesium atoms as probes, to achieve accurate magnetic field mapping inside UHV, essential for ensuring the accuracy of cesium fountain clocks.

The clock transition $\left|F=3, m_f=0\right\rangle \rightarrow \left|F=4, m_f=0\right\rangle$ shows minimal sensitivity to the magnetic field changes with a small frequency shift proportional to $\left\langle B^2 \right\rangle$, the mean squared magnetic field averaged over the flight region above the microwave cavity. To precisely measure the magnetic field strength, linear Zeeman frequency shift of magnetically sensitive transitions $\left|F, m_f \neq 0\right\rangle$ is measured. In general, Zeeman shift is measured by measuring the shift in the central fringe for the $\left|F=3, m_f=1\right\rangle \rightarrow \left|F=4, m_f=1\right\rangle$ transition which has a linear dependence on the magnetic field B. Using the Breit-Rabi formula, the second-order Zeeman shift can be calculated, where the first term predominates and adds a bias to the fountain frequency. The uncertainty of the 2nd order Zeeman shift is given by the temporal instability of $\left\langle B \right\rangle$.

$$\frac{\Delta \nu_{2nd\,Zeeman}}{\nu_0} = -8 \cdot \left(\frac{\nu_{1-1}}{\nu_0}\right)^2 + 427.45 \times 10^8 \cdot \frac{\sigma^2}{\nu_0} T^2 Hz^{-1}$$

By launching atoms at various heights within the ultra-high vacuum (UHV) chamber, the shift in the central Ramsey fringe is measured. The fluctuations in the magnetic field are proportional to the fringe shift. The magnetic field profile is then reconstructed using the deconvolution method, which integrates average magnetic field values with ballistic time of flight data. This method enables precise mapping of magnetic field variations using the Zeeman offset derived from the Breit-Rabi formula. Thus, measuring the frequency shift of the central fringe as a function of launch height effectively maps the magnetic field, with cold- atoms serving as quantum magnetic field sensors.

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