INTEGRATION OF HIGH-RESOLUTION FREQUENCY CONTROL AND THERMOMETRY FOR HIGH-PRECISION MEASUREMENTS OF PHYSICAL PROPERTIES OF HELIUM

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Modern technologies of high-resolution frequency control and high-resolution thermometry (HRT) make it possible to perform state-of-the-art precision density measurements of liquid helium[1]. In a superconducting niobium microwave cavity with a high quality factor ($Q \sim 10^9$ at 2.2K) and filled with helium, the shift in the cavity resonant frequency provides direct information for the changes in the dielectric constant which is related to the density of helium through the Clausius-Mossotti relation. With a resolution in frequency measurements up to one part in 10^{16}, and a resolution in thermometry[2] to one part in 10^{11}, density changes to one part in 10^{11} to 10^{12} can be resolved in the microgravity environment, which makes it possible to study critical phenomena to an unprecedented precision. In this paper, we present our experimental development on integrating these technologies for ground-based measurements. To achieve high-resolution frequency control, the phase-locked loop technique is used to lock the output frequency of a low-noise microwave signal source to the resonant frequency of the superconducting cavity. This technique, which essentially integrates a superconducting-cavity-stabilized-oscillator (SCSO), provides a resolution of one part in ($10^7 \times Q$). A quality factor Q of 10^9 therefore gives a resolution of one part in 10^{16}. The locked frequency is then compared with a high stability frequency standard which provides both the stability and accuracy for the frequency readout. Ultimately, a stability of one part in 10^{15} to 10^{16} can be realized by comparing with a second similar SCSO. An accuracy of one part in 10^{14} is achievable using the cesium beam frequency standard at the National Institute of Standard Technology (NIST) and applying precise time transfer through the global positioning system[3] (GPS). We will report our progress on implementing these techniques by demonstrating (i) the quality factors of niobium cavities fabricated in our lab using ultra-high vacuum annealing at high temperatures, (ii) the performance of the phase-locked loop system, and (iii) the resolutions in the frequency readout using a portable cesium standard for a range of measuring times. In addition, analyses will be given on the constraints of various thermal, electrical, and mechanical noises in the system for our high-resolution frequency measurements. To achieve the high resolutions in temperature control and readout, the high-resolution thermometer based on DC-SQUID magnetometry[2] is implemented in our system. We emphasize that with our frequency control and readout techniques, the resolution in thermometry becomes the main limiting factor to the overall resolution in our measurement of helium density and related properties. Preliminary data will be presented for the purpose of illustration of our experimental approach.

[1]N.-C. Yeh, W. Jiang, D. M. Strayer and N. Asplund, Czech. J. Phys., v46, Supplement 1, 181 (1996).
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[3] Reference for GPS.