Progress Towards a Transportable and High-Accuracy Sr^+ Ion Clock at NRC

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***Abstract*—We are developing a transportable $^{88}Sr^+$ ion clock for frequency comparisons with optical clocks in remote laboratories. Accuracy limitations found in the current NRC laboratory system, most notably the uncertainties related to the blackbody radiation shift and the collisional frequency shifts, should be significantly reduced in the new system. The expected total systematic fractional frequency uncertainty of the device approaches the 10^{-18} level.**

Keywords*—*ion optical clock; ion trap design; blackbody radiation shift

I. Introduction

To obtain the full accuracy potential of optical clocks it is essential to compare independent devices with uncertainties comparable to their evaluated uncertainties. This provides validation of their actual performances and is the basis for establishing a consistent worldwide network of optical frequencies in view of a re-definition of the SI second [1].

Frequency comparisons at the 10^{-16} level have been demonstrated using convenient and widely available GNSS satellite links [2], [3]. This method, however, is insufficient for the comparison of optical clocks with fractional uncertainties at the desired goal of 10^{-18}. Although optical fiber links are available for intercomparison of optical clocks at their full potential, they are not universally available and are presently nonexistent for intercontinental comparisons [4]. Transportable systems are often the only alternative for clock comparisons at the highest level of accuracy with remote laboratories.

We are developing a transportable Sr^+ ion clock for high-accuracy frequency comparisons with remote optical clocks. The target form factor of the transportable system has a volume of 1.8 m^3. Extrapolating from the observed stability of our laboratory single ion clock of $3 \times 10^{-15}/\sqrt{\tau/s}$ [5], optical frequency ratio measurements with an uncertainty of $\approx 5 \times 10^{-18}$ should be achievable with this device in approximately one week of averaging time.

The $5s\,^2S_{1/2}$–$4d\,^2D_{5/2}$ electric quadrupole transition of the $^{88}Sr^+$ ion is well-suited to realize compact and high-accuracy optical clocks. The simple energy level structure requires only four wavelengths for operation of the clock. If photoionization loading is used, two additional laser wavelengths are required. A significant simplification of the laser systems is realized by replacing the repumper and clearout laser systems with very compact broadband amplified spontaneous emission (ASE) sources that do not require frequency stabilization [6].

The high-accuracy of the $^{88}Sr^+$ ion clock can be achieved without sacrificing compactness and simplicity of operation. The main sources of uncertainty for the $^{88}Sr^+$ ion clock are the blackbody radiation (BBR) shift, the micromotion shifts, the electric quadrupole shift, and the collisional shifts. The BBR shift uncertainty is addressed with a new ion trap design that reduces significantly ion trap heating effects. The micromotion shifts are strongly suppressed by operating the trap at the "magic" rf drive frequency where the Stark and second-order Doppler shifts cancel each other [7]. Finally the electric quadrupole shift is canceled to extremely low levels using a Zeeman averaging method [8].

The ion trap and vacuum system designs provide the main improvements to the frequency uncertainty compared to the current NRC laboratory clock. These topics are discussed briefly below.

II. Ion trap design

The ion trap used in the NRC laboratory optical clock uses machinable ceramic as the support structure as shown in Fig. 1. The poor thermal conductivity of this material prevents efficient removal of the heat produced by the rf voltages and currents. In addition, the rf endcap electrodes were fabricated from small molybdenum wires of 0.5 mm diameter that cause significant Joule heating [9]. They are insulated from the concentric shield electrodes using 1 mm diameter alumina tubes that have a wall thickness of 0.25 mm. The alumina spacers increase the capacitance between the electrodes and therefore rf currents and Joule heating in the conductors. The alumina material also contributes heating from the material losses at rf frequencies. In contrast, the new system shown in Fig. 2 uses a high thermal and electrical conductivity copper alloy C-shaped structure to carry the rf currents. It has a 10 mm square section at the base where it connects to a 6 mm diameter copper feedthrough conductor. The fused silica insulators between the shield electrodes and the copper alloy post are 3 mm thick, and have low loss tangents that further minimize heat generation. The endcap electrodes have a diameter of 0.75 mm at the tip that increases to 3 mm before contacting to the copper alloy structure for improved electrical and thermal conductivity. None of the high-emissivity dielectric materials in the trap and vacuum system will have a direct optical path to the ion position for minimized black body radiation (BBR) shift. Based on

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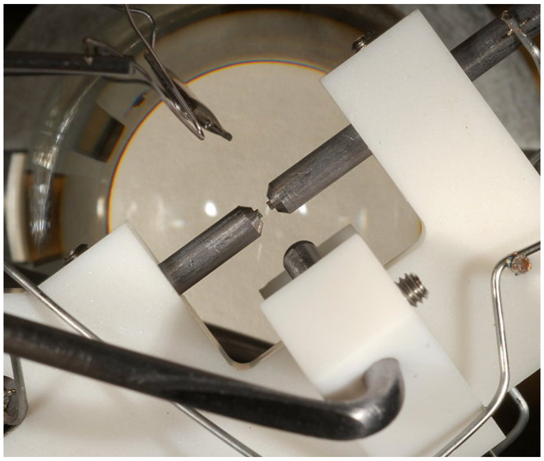

Fig. 1. Picture of the current $^{88}Sr^+$ ion trap at NRC [9].

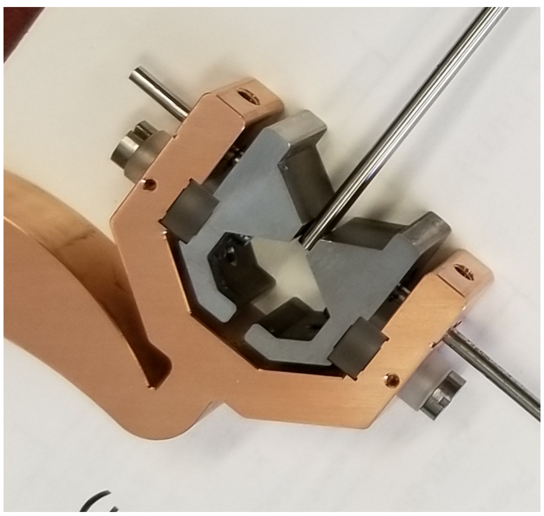

Fig. 2. Picture of the partially fabricated new ion trap for the transportable system showing initial tests of the machining tolerances. The endcap electrodes are missing in this image and the shield electrodes will be machined into a conical shape near the trapping region. The measuring bar between the shield electrodes has a diameter of 1.8 mm.

previous work using comparable design materials, we expect the BBR shift and its uncertainty to be reduced by at least one order of magnitude in the new system [10], [11]. Careful evaluation should allow for further reduction of the BBR shift uncertainty.

III. Vacuum system

The vacuum system for the transportable clock uses a simple geometry that aims to maintain high pumping speeds. To get an estimate of the reduction of the H_2 pressure at the position of the ion in the new system compared to that of the existing NRC ion clock, we carried out numerical simulations of the vacuum pressures based on the vacuum geometries and pumping speeds [12]. This preliminary analysis shows that the H_2 partial pressure in the new system should be an order of magnitude lower than in the current system, assuming that the outgassing rates are the same in both cases. A lower background pressure will yield smaller collisional frequency shifts and better clock operation uptimes.

IV. Conclusions

The transportable $^{88}Sr^+$ optical clock built at NRC is expected to have a significantly lower uncertainty than the current laboratory optical clock because of an improved rf trap design that minimizes blackbody radiation shifts. The new vacuum system design with higher pumping speeds should also result in longer clock uptimes and reduced collisional frequency shifts. The accuracy of the transportable system is not compromised by the smaller size of the device. The control of the systematic shifts benefits greatly from the Zeeman averaging method of canceling the electric quadrupole shift and from operation of the ion trap at the magic frequency of 14.4 MHz that allows a strong reduction of the micromotion shifts. Neither of these methods require physical components. The expected uncertainty of the transportable clock is slightly below 2×10^{-18}. An uncertainty of $\lesssim 10^{-18}$ is possible with the $^{88}Sr^+$ ion, but would require the implementation of ground state laser cooling and a more accurate determination of the differential scalar polarizability and of other small frequency shifts.

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