Development of high-accuracy Sr^+ optical clocks for the re-definition of the SI second

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Several mandatory criteria must be fulfilled before the SI second can be re-defined using optical frequency standards.[1] The criteria directly relevant to the performance and evaluation of the optical frequency standards (optical clocks) are an uncertainty budget with a relative frequency uncertainty of $\lesssim 2 \times 10^{-18}$, a validation of the optical frequencies using unit and non-unit frequency ratios at the level of $\lesssim 5 \times 10^{-18}$, and continuity with the current definition of the SI second with a fractional uncertainty $\lesssim 3 \times 10^{-16}$.

Two new room-temperature single-ion optical clocks are being developed at the NRC. One will be used in a transportable system and the other will be used in the laboratory. These clocks use nearly identical ion trap and vacuum chamber designs. The design of the new optical clocks addresses the most important systematic frequency shifts encountered in our current laboratory ion clock.[2] The primary sources of uncertainty in this system are the blackbody radiation shift (BBRS) with a contribution of 1.1×10^{-17}, and the collisional frequency shift (CFS) with a contribution of about 2.6×10^{-18}. All the other frequency shifts in the uncertainty budget are below the 10^{-18} level.[2]

The ion trap design used in the new optical clocks significantly reduces the heating sources.[3] Recent measurements indicate that the temperature increases in the room temperature clocks are about 20 times smaller than in the current NRC laboratory ion clock. The background gas pressure is reduced using an improved design of the vacuum system and a baking treatment of the steel components that removed most of the hydrogen. We expect that the background gas pressure in the new systems will be reduced by about an order of magnitude compared to the current system. The total fractional uncertainties of the new room-temperature $^{88}Sr^+$ optical clocks are expected to be $\lesssim 1.6 \times 10^{-18}$, thus satisfying the first criterion.

The ion trap in the cryogenic $^{88}Sr^+$ clock developed at the University of Toronto will be operated at a temperature of 4 K. At this temperature, both the BBRS and the CFS are negligible. The expected fractional uncertainty of the cryoclock is below 10^{-18}.

The transportable system will be used for comparisons with optical clocks in other laboratories to satisfy the second criterion. Based on the demonstrated stability of the current laboratory optical clock, a fractional uncertainty of $\lesssim 5 \times 10^{-18}$ can be achieved in about 8 days of measurement.

Finally, we made a preliminary measurement of the $^{88}Sr^+$ ion clock frequency using the NRC-FCs2 cesium fountain clock. The fractional uncertainty is estimated to be 2.2×10^{-16}, thus meeting the third criterion. We plan on making more extensive measurements later this year to reduce the uncertainty below 2×10^{-16}.

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[1] N. Dimarcq *et al.*, "Roadmap towards the redefinition of the second," *Metrologia*, vol. 61, no. 1, p. 012001, 2024.

[2] B. Jian, J. Bernard, M. Gertsvolf, and P. Dubé, "Improved absolute frequency measurement of the strontium ion clock using a GPS link to the SI second," *Metrologia*, vol. 60, no. 1, p. 015007, 2022.

[3] P. Dubé, K. Kato, S. Smale, and A. Vutha, "Development of room temperature and cryogenic strontium ion clocks with low uncertainties," in *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, pp. 1–2, 2023.