How to rebuild an atomic clock

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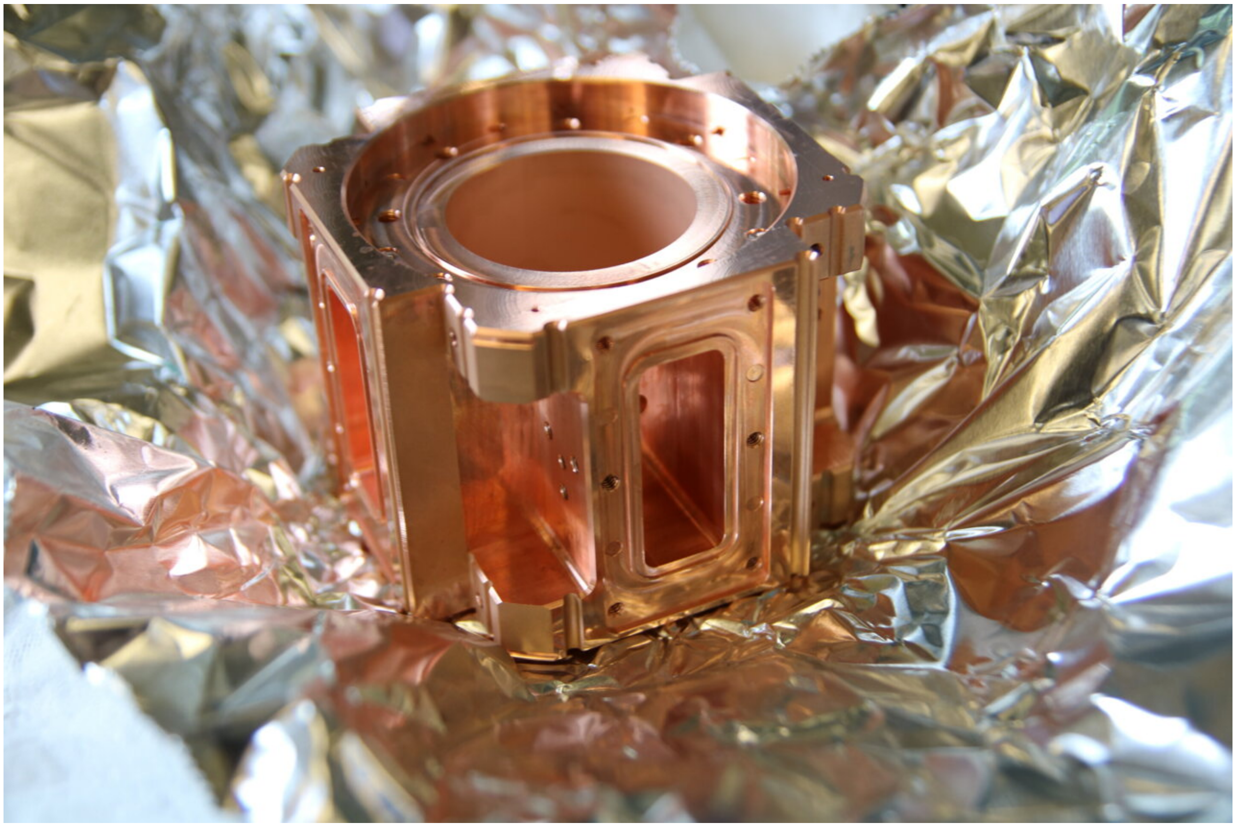

Credit: University of Colorado at Boulder

Atomic clocks are crucial for everyday living as they help our telecommunications, electrical power grids, GPS systems, transportation, and other processes around the world keep precise time. Some of these clocks use lasers and special resonator cavities to measure time intervals. They are some of the most accurate clocks in the world and the most fragile.

The cesium atomic clocks play a consequential role, as a specific atomic transition induced in the atomic cesium is used to define the unit of time: the SI second. The National Institute of Standards and Technology (NIST) laboratories in Boulder, Colorado have housed atomic clocks—including the cesium atomic clock NIST-F1 which serves as the United States' primary time and frequency standard—for decades, as researchers continue to improve the clocks' accuracies through cutting-edge research. For the NIST-F1 cesium clock specifically, this process has included rebuilding parts of the clock.

The NIST-F1 clock is also called a "fountain clock" due to the fountain-like movement of the cesium atoms inside the clock that is used to measure time intervals. These cesium atoms begin in a special vacuum chamber, where six infrared laser beams herd the free-flying atoms into a ball. During the creation of this ball, the system is cooled to near absolute zero (zero Kelvin) to slow down the movement of the atoms.

After cooling, two vertical lasers toss the ball of cesium atoms into an upward arc (the "fountain") and then all laser beams are shut off. The cesium ball moves upwards for about a meter in a special microwave-filled cavity, which may alter some of the atoms within the ball. The ball then drops, and again, the microwave field may interact with the atoms, causing more of them to change their state. The final atomic state is determined by measuring the fluorescence of the altered atoms induced by another laser beam.

The entire process takes around one second, and is repeated multiple times to find the right frequency that excites the specific clock transition of the cesium atoms. Once the microwave frequency is found, at which the microwave signal interacting with the cesium atoms would cause a maximum amount of them to change their state (at maximum fluorescence), that frequency is then used to define a second of time by counting exactly 9,192,631,770 signal periods (found by the scientists) with a counter. This definition is then applied to other clocks for calibration and accurate timekeeping.

The microwave cavity is a crucial piece of the timekeeping process, and researchers at NIST hoped to improve the accuracy of the clock by rebuilding the entire cavity. "We had issues with the previous clock cavity that limited the clock's accuracy," explained NIST scientist Vladislav "Vladi" Gerginov. "One of the issues was with the cavity's material (aluminum)."

As atomic clocks are extremely sensitive to imperfections in the cavity shape, electrical conductivity, and polish, the cavity's materials have to be made of the right material, and have the exact shape, size and finish for minimizing clock inaccuracies. "One of the crucial steps in building a cesium clock is tuning the frequency of the cavity to match the transition frequency of cesium," explained instrument maker Calvin Schwadron of JILA (a joint institute between NIST and the University of Colorado Boulder). "The frequency that a microwave cavity resonates at depends on the volume inside of it."

To do this, the researchers leaned on the expertise found a JILA. According to Curtis Beimborn, Head of the W.M. Keck Metrology Lab and Clean Room at JILA, "The quality of the cavity (Q) is very important to improve the clock's performance."

To increase the cavity's Q, Gerginov collaborated with the machine and instrument shops at JILA, using the instrument shop and clean room to build the new microwave cavity out of copper. "It's incredibly rare to have a full shop collaboration like this," stated JILA instrument maker Adam Ellzey "All six of us sat in with Vladi during design consultations. In the fabrication stage, we're all regularly checking in with each other to make sure our parts fit and our designs agree. Making components of a clock that will be the nation's time standard is a big deal that has taken some real thought. It's been amazing to watch my fellow instrument makers flex their expertise. I've learned a ton."

The JILA instrument shops are a key factor in making JILA a unique research institution. According to Kyle Thatcher, head of the instrument shop, "The real value of the JILA Instrument Shop is that scientists get the opportunity to work directly with instrument makers to realize their experimental apparatus. This means that from conception, scientists are able to collaborate on the design, engineering, fabrication, and testing of their device utilizing the shop's vast accumulated institutional knowledge. Additionally, with the Instrument Shop's open-door policy, and being in such close proximity [in the building for the case of JILA], allows for very quick iterative development, troubleshooting, and device modification [and] repair."

This process of close collaboration between scientists and instrument makers is rather rare to find in most research institutions, as traditionally, instrument makers work off designs provided by the scientists with very little back and forth, as Thatcher explained. At JILA, the collaboration afforded between the in-house shops and the scientists allows for custom-built instruments that are found nowhere else. This includes the parts for the NIST-F1 cesium clock.

"The Instrument Shop was able to work with Vladi and his colleague to help optimize critical features of the system including material selection, component reduction, serviceability, and design for manufacturing," explained Thatcher. "More importantly, however, was the ability of Vladi to set up his test equipment from NIST within the shop where he was able, practically in real-time, to quantify the performance of parts being made thus enabling the manufacturing processes to be tweaked on the fly improving results."

The process of creating a new cavity involved many different steps, including an ongoing back and forth between Gerginov and the machinists on the design of the cavity. After initial testing of the new copper cavity, the Q was roughly a factor of three lower than what was expected and Vladi suspected that the metal surface finish inside the cavity may be the culprit since the microwave frequency currents are confined to the surface of the metal, instead of traveling through the bulk [walls].

"Calvin and Vladi brought it down to the Optical Metrology Lab, and I measured the surface roughness for them using our optical profilometer," Beimborn stated. "Sure enough, the roughness was great enough that all the tiny surface imperfections were adding quite a lot to the distance the microwave frequency currents were traveling in the cavity, which diminished the Q factor. After this measurement, Calvin polished the interior of the cavity and I believe Vladi saw a factor of two improvements in the Q right away."

Thanks to NIST's close collaboration with JILA, the new cavity will help get the NIST-F1 Cesium clock back to work. As Elizabeth Donley, NIST's Time and Frequency Division Chief said, "The cavity machining in the JILA shop has been a very important part of the work to bring the fountain back online and we're very grateful for that. It's been great to have the JILA shop as such a valuable local resource."

With the clock up and running, NIST researchers can continue to work on pushing the boundaries of atomic clock physics. "The clock will be used at NIST to calibrate the official NIST timescale, as well as other atomic clocks and frequency references," Gerginov added.

Provided by University of Colorado at Boulder

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