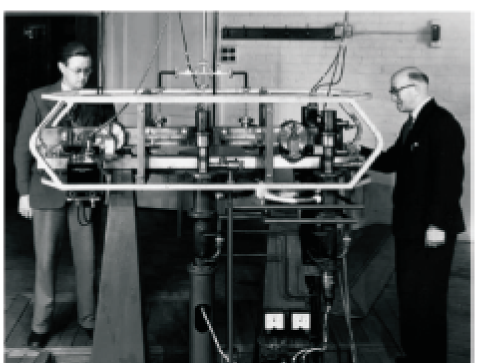
MSI newsletter. vol1. No.1. 2011. metrologyindia.org

Brief History of Cesium Atomic Frequency Standards

At the present time, among all physical quantities, time interval and frequency are the ones that can be measured with the highest precision and accuracy. Conceptually, the measurement of time is simple: we take a stable periodic phenomenon with a period that is much shorter than the time interval to be measured. In this case the measurement of time interval or establishment of time scale can be reduced to counting cycles of this periodic phenomenon. Historically the best long term stability was provided by rotation of celestial bodies and indeed the rotating earth still provides our everyday feeling for time. However, the great progress in the accuracy of time measurement in the last five decades or so has come from the use of atomic resonance frequencies. This fundamental concept of using atomic frequency standards and clocks was first proposed by James Clerk Maxwell, in his 1873 treatise. He wrote "...If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules". There was no way to realize this excellent idea in 1873, but beginning in 1937 a series of inventions and developments eventually made atomic frequency standards possible.

Atomic beam magnetic resonance frequency standards and clocks were the first high precision standards and they are still used for the international definition of the second and for many precision measurements. These clocks grew out of the molecular beam magnetic resonance method which was invented by I.I. Rabi in 1937. The first experiments on atomic hyperfine transitions changing the value of F ($F = I + J$) were observed in 1940 by Rabi and his group in Columbia University, including the famous Cesium (Cs) ground state hyperfine transition (9.192 GHz) that is now used for atomic clocks. The next major improvement of accuracy of the atomic frequency standards was made in 1949 by Norman Ramsey, who invented the methods of separated and successive oscillatory fields. The first working Cs atomic frequency standard that contributed to a national time and frequency standards was constructed in 1955 by Essen and Parry at the National Physical Laboratory in England. From 1956 onward many Cs atomic clock improvements were developed at universities, national laboratories and industries around the world. The Cesium clock has since started becoming available worldwide as a commercial product.

Dr. A. Sen Gupta
Scientist 'H'
NPL, New Delhi



L. Essen (on right) with the first Cs atomic frequency standard developed by him

In 1967 the unit of time, the second, was defined in terms of the Cs hyperfine oscillations. Subsequent international agreements provided an international UTC (Universal Time Coordinated) based on atomic time but with leap seconds introduced whenever necessary to keep UTC within 0.7 seconds of GMT (Greenwich Mean Time) as determined by astronomical observations. In subsequent years up to the present the accuracies of the best Cs beam clocks have steadily improved and the unit of time continues to be defined in terms of the Cs frequency.

Best accuracies achievable in the Cs beam standards as discussed above were limited to about 10^{-14} due to the short interaction time between the microwave interrogating signals and the thermal atoms due to their large velocities. A major breakthrough was made in the late eighties by Steven Chu at Stanford and early nineties by Andre Clairon's group in BNM, Paris by employing a cloud of laser cooled atoms and launching the atoms vertically upwards. This is the so called Cs fountain in which it is possible to enhance the Cs-microwave interrogation time to about half a second, thus resulting in achievable accuracies of the order of 10^{-15}. In the last decade or so several Cs fountains have been made in National Metrology Institutes (NMIs) around the world, such as, NIST (USA), PTB (Germany), BNM (France), NPL (UK) etc. At present these fountains majorly contribute to the determination of the rate of UTC maintained by BIPM in Paris.

Although present-day Cs microwave frequency standards perform at an already remarkable level, a new approach to timekeeping based on optical atomic transitions promises still greater improvements. By using optical ($\sim 10^{15}$ Hz) rather than microwave ($\sim 10^{10}$ Hz) frequencies results in five orders of improvement. However, the optical standards are mostly based on single trapped ion that can be laser-cooled to the zero point of its motion, thereby suppressing Doppler effects that can shift the resonance frequency. Use of single ions as opposed to a cloud of a few million atoms (as in a Cs fountain) results in a loss of signal to noise. This can be fortunately made up by using large interrogation times as the lifetime of the trapped ion is typically longer than days. Optical standards can thus be considerably more stable and accurate as well, as several key frequency shifts are fractionally much smaller in the optical domain. Outstanding performances have already been demonstrated with optical transitions in a variety of single-ion systems, including Hg^+, Yb^+, Sr^+, In^+, Al^+ etc. It is anticipated that in the coming years the systematic effects in a few single-ion optical frequency standards could be controlled at a level that would permit accuracies of these clocks approaching an unprecedented 10^{-18}. A natural consequence of such a development would be the consideration by the BIPM of redefining the SI second in terms of an optical transition instead of the present 9.192631770 Ghz Cs transition.

Research on atomic frequency standards at NPL, India has been pursued in right earnest in the last five years or so. At present we have just completed the development of a Cs fountain – the first in the country and among less than ten in the world. We are also undertaking an ambitious research project on optical frequency standards based on single trapped ions in the coming years.