White paper

Cesium beam clocks: magnetic versus optical technology

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Cesium beam clocks are the most stable and accurate industrial frequency sources for long-term applications. For decades and among various manufacturers, clocks have traditionally operated by means of magnetic deflection. With the commercial availability of narrow-band laser sources, optical pumping can now replace cesium clock designs. In this paper, we will review the differences between these two designs, focusing on their unique advantages and disadvantages.

Why use a cesium clock?

Since 1967, the International System of Units (SI) has defined a second of time as the duration of 9,192,631,770 oscillations between both hyperfine levels of the unperturbed ground-state of the cesium 133 (^{133}Cs) atom. Prior to this, a second of time was defined as a fraction of the Earth's daily rotation period, which was no longer precise enough for some applications (typically one millisecond/day or 1E-8 in fractional value). The cesium-based definition of time brought about several new constraints:

1. The use of a particular atom, namely ^{133}Cs, which is stable and therefore a non-radioactive element
2. Probing this reference atom in the RF frequency domain (GHz)
3. The probe frequency must equal the unperturbed ground state of the ^{133}Cs atom

The choice of ^{133}Cs atom was made according to several criteria, including resonance frequency, intrinsic stability and environmental sensitivities. Although other types of atoms can be used to build feasible atomic clocks (e.g., rubidium vapor cell or hydrogen maser), long-term frequency stability and accuracy are best defined by the ^{133}Cs atom.

The requirement to probe the frequency of its unperturbed ground state offers some subtle clues on the design of the atomic resonator. While rubidium and hydrogen masers are cell-based standards, they suffer from wall-cell proximity, impacting their thermal sensitivity and long-term stability by residual frequency drift. In contrast, cesium is commonly designed as a beam standard that prevents the interaction of atoms with the container wall and mitigates both its thermal sensitivity and frequency drift.

Nonetheless, other environmental sensitivities remain and must be controlled with the highest level of accuracy:

- Magnetic field – which is non-uniform across the surface of the Earth
- Electric field – microwave interference generated from other electronic devices
- Gravity field – influenced by the location and height on Earth due to relativistic effects

When relying solely on clock output frequency stability (syntonization), the effects can be stable but also inaccurate. For applications relying on the time instead of the frequency (synchronization), it is imperative that the atomic clock output frequency be sufficiently stable ("not varying with time") and be accurate ("be as close as possible to the definition value"). This is required because the timing signal is generated simply from counting the clock frequency. If the clock frequency is inaccurate, the generated timing signal will also be incorrect by either being too slow or too fast.

The technical definition features validate why the cesium beam standard is crucial for use in all long-term and accurate frequency applications such as positioning, navigation and timing (PNT), metrology, time scales, synchronization in defense, telecommunications, remote databases, finance, power utilities, industrial, academia and more.

How does a radio-frequency atomic clock work?

The operating principle of a radio-frequency (RF) atomic clock is shown in Figure 1. Before analyzing it, let's focus on the quantum model of the atom (inside the dashed line). This model is greatly simplified and does not represent particular atoms like H, Rb, or Cs. Despite the minimal details, the diagram still helps to convey the differences in operation between a magnetic and an optical clock:

- All lines labeled *a*, *b* or *e* are quantum energy levels in which the atom under test must remain.
- Levels *a* and *b* are called the ground states and are infinitely stable: an atom staying in these states will never escape unless a dedicated perturbation is applied. The energy difference between the ground states *a* → *b* is Eg and is proportional to the frequency ν.
- Level *e* is considered excited and is very unstable: an atom staying in this state will almost immediately fall into one of the ground states. To bring an atom initially in the ground state *a* to the excited state *e* is achieved by providing it with an energy quantum Ee, which usually corresponds to a light photon absorption of wavelength λ. From the excited state *e,* if the atom falls to the ground *b*, this atom becomes transparent to the laser light which is tuned to the *a* → *e* transition; on the contrary, if it falls back to the ground state *a* where it comes from, it can repeat its photon absorption. After a limited number of cycles, all atoms from the ground state *a* will have moved to the ground state *b* by this optical pumping process via the excited state *e*.

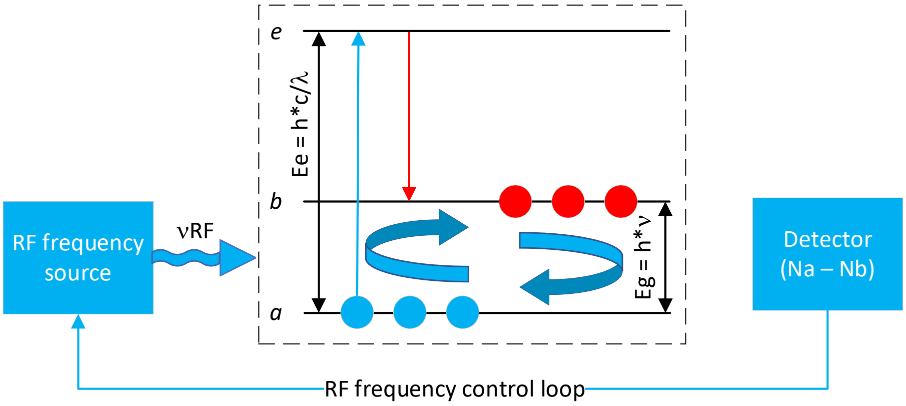

Figure 1: Atomic clock principle: the RF frequency source shines a microwave signal νRF on a two-level atom of ground states a and b of eigenfrequency ν. When νRF is offset from ν, the detector computes an error signal provided by the atoms number difference in both ground states that is fed back to control the RF frequency source. The excited state e is only used with optical pumping technology.

When shining an RF signal of frequency νRF resonant with the atom eigenfrequency (or natural frequency) ν (νRF=ν), atoms laying in the ground *a* will move up to the ground *b* and atoms in the ground *b* will fall in the ground state *a*. As the detector is sensitive only to the difference of the particle number (Na-Nb), if both ground states are equally populated, the system will not receive a useful signal to correct the RF frequency source. However, if one of the ground states is more populated (or, in the best case, if the other ground state is entirely depopulated), the detector will get a net error signal sensitive to the frequency matching νRF to ν. Therefore, such an error signal can be used to actively control the RF frequency source to the atomic reference frequency.

Is an optically pumped cesium clock a quantum atomic clock?

Yes. An optically pumped cesium beam clock has all the components and features of a quantum atomic clock:

- It uses cesium atoms that must be described by their quantum model (discrete energy levels) to properly understand and manage its operation and performance.
- It uses optical pumping technology to prepare and detect the atomic transition occurrence.

Magnetic-deflection versus optical pumping

Any of the atomic beam tubes, whether magnetically deflected or optically pumped (see Figure 2), feature an oven that contains several grams of alkali metal (^{133}Cs in our case) and a capillary tube assembly to produce an atomic beam. When heated, the oven generates an atomic beam that is equally populated with atoms in both ground states. To achieve this population difference between the ground states, there are two possibilities:

- *Magnetic deflection* (Figure 2a): by crossing the atomic beam of a pair of magnets with an anisotropic magnetic field (magnets of different shapes), atoms in the ground state *a* deviate to their right, while atoms in the ground state *b* deviate to their left – and are then redirected through the RF cavity. This selection by magnets depopulates the ground state *a* and creates the required imbalance described above. Although simple, this technique has two main limitations: first, the atoms in the ground state *a* are lost after the first pair of magnets; second, only a small fraction of the beam (narrow velocity spread) can properly make the required turn in with the magnets. Consequently, the useful atomic flux crossing the cavity is relatively weak, which limits the clock performance (frequency stability) for a given tube lifetime (alkali load in the oven).

- *Optical pumping* (Figure 2b): to overcome this lack of efficiency of the magnetic deflection process, a laser light–atom interaction delivers an innovative and efficient solution. Thanks to the optical pumping process described above (Figure 1), all atoms of the atomic beam in the ground state *a* are brought to the ground state *b* providing that the laser light exactly matches the wavelength corresponding to the transition *a* → *e*. The two main limitations of the magnetic deflection are now overcome: first, no atoms from the atomic beam are lost; second, atoms of almost all velocity are pumped (wide velocity spread). It implies that for the same tube lifetime (same load of alkali in the oven), an atomic flux typically increases by two orders of magnitude and consequently, a clock frequency stability boosted by a factor of five to ten.

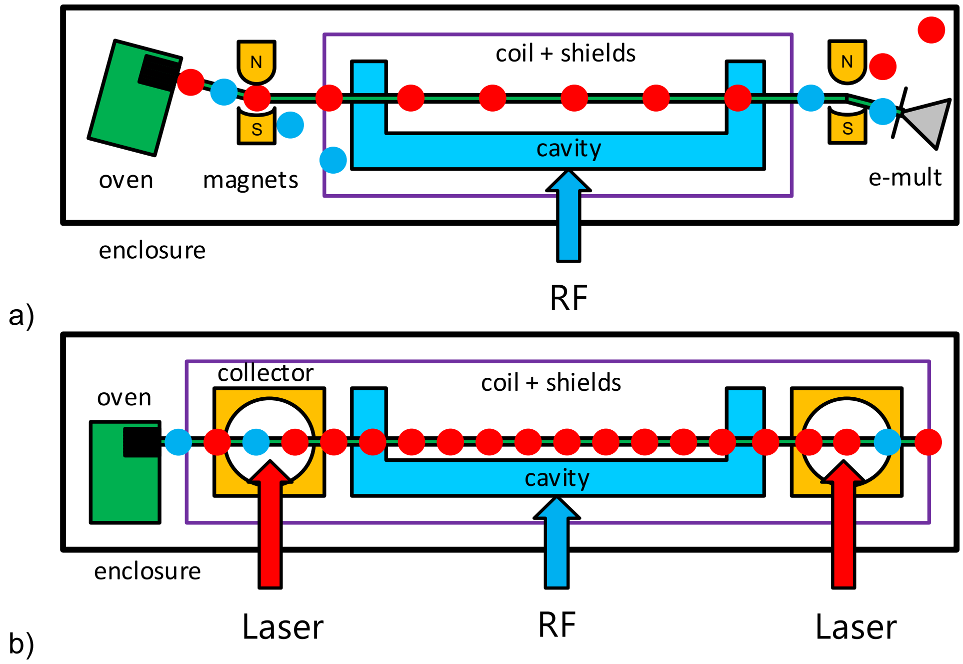

Figure 2: a) Magnetic-deflected atomic beam tube: thanks to the magnetic field gradient (N and S magnets), atoms in the upper ground b are redirected towards the U-shape cavity. In contrast, atoms in the other ground state are deflected off-axis and are lost.
b) Optically pumped atomic beam tube: thanks to the laser at optical resonance, atoms in the ground state a are moved to the ground state b without any loss of atoms.

Table 1 summarizes the main features of both clock technologies, namely the magnetic cesium clock OSA 3230B and the optical cesium clock OSA 3300-HP. The two main advantages are:

1. Significant increase of useful flux for the optical clock (about 100 larger than the magnetic clock). This comparison is made for the same Cs oven temperature, which yields the same tube lifetime. This useful flux increase directly improves both the clock frequency stability and accuracy.

2. Critical components: while both designs utilize a critical component at the physics package level, the laser of the optical clock is located in the air, is redundant, and can easily be replaced, while the electron multiplier on the magnetic clock is placed under vacuum in the beam tube and cannot be replaced. This is a significant advantage for the maintenance of the optical clock.

The optical clock might suffer from a new environmental sensitivity. By the presence of some resonant light in the optical clock, which is absent in the magnetic design, the atomic reference frequency will be slightly shifted upon the power, the wavelength and the propagation direction of this light. This effect is commonly known as “light frequency shift.” If not properly controlled, the clock’s long-term stability and accuracy could become impaired. However, with a proprietary algorithm we have developed (Oscilloquartz patent pending), this light shift can be greatly minimized.

Parameter	Magnetic clock (OSA-3230B)	Optical clock (OSA-3300 HP)
Tube lifetime	10 years	10 years
Cs oven temperature	100 °C	100 °C
Cavity length	12 cm	12 cm
Nr magnetic shields	2	2
Tube length	Fit in 19’’, 3U rack	Fit in 19’’, 3U rack
Nr digital servo loops	5	8
Useful atomic flux	F_{magn}	$F_{opt} = 100 * F_{magn}$
Short-term stability (t = average time)	$2.7E-11\ t^{-1/2}$	$8.5E-12\ t^{-1/2}$
Long-term stability	5E-14	1E-14
Accuracy	1E-12	5E-13
Critical component	Electron multiplier (in a vacuum, not redundant and not replaceable)	Laser (in air, redundant and replaceable)

Table 1: Comparison of magnetic and optical clocks parameters

To improve the short-term stability of the magnetic cesium beam clock while keeping the exact clock dimensions it is necessary to increase its cesium oven temperature. This allows the magnetic technology to reach the HP short-term stability but with a significant lifetime reduction of five years instead of ten. Moreover, this higher oven temperature (130°C = 266°F) represents a **maximum technological limit for the Cs tube operation,** which also means a maximum limit for short-term stability.

On the other hand, with optical pumping technology, HP performance is already reached at normal oven temperature (100°C = 212°F), which enables either the long Cs tube lifetime to be maintained or frequency stability to be further increased by simply increasing the Cs oven temperature, meaning the OSA 3300-HP in temperatures over 130°C (266°F) will further outperform magnetic cesium models.

Clock performance

To compare the performance of both cesium beam clocks, their electrical output signals are compared in phase to that of one of a better reference clock (hydrogen maser). Figure 3 shows two kinds of metrics:

- In Figure 3a, the overlapped Allan deviation of the fractional frequency is plotted as a function of the averaging time. The vertical axis measures the standard deviation or root mean square value of the clock output frequency signal. The longer the averaging time, the lower the deviation, which shows that the longer the clock is measured, the more certain we are about the accuracy of its output signal. The vertical offset between the two curves demonstrates that Cs optical clocks perform about five times better than magnetic clocks. Both clocks largely comply with their respective specifications: Cs magnetic to standard performance (SP) line and Cs optical to high performance (HP) line.

- In Figure 3b, the same measurement data are used, but they are represented as the time interval error (TIE) for each of the Cs clocks as a function of the passing time.
  Both clock measurements largely comply with their specifications: Cs magnetic with enhanced primary reference clock (ePRC) and Cs optical with the super-enhanced primary reference clock (SePRC).

With those measurements, we can see the superiority of the optical Cs clocks compared to the magnetic Cs clocks, both in terms of frequency stability (low 1E-15 range) and in terms of timing error (±10 ns for 60 days of operation). Oscilloquartz products deliver the best performance recorded for an industrial cesium beam clock.

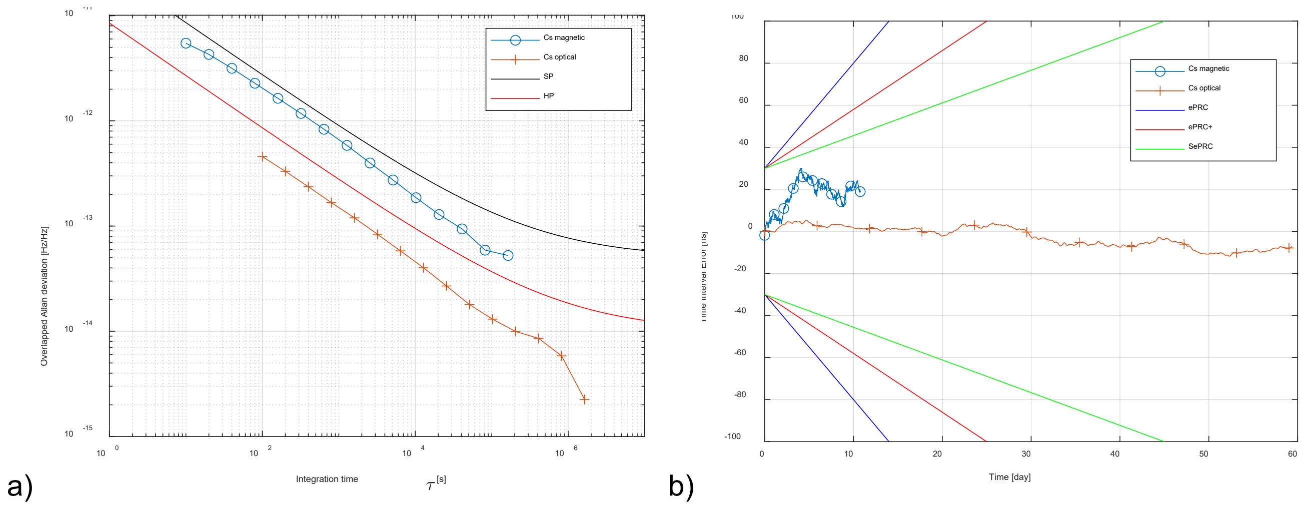

Figure 3: Clocks performances comparison: a) Frequency stability; b) Time interval error

Biography

Dr. Patrick Berthoud earned his education as a Physics Engineer from EPFL, Switzerland. He received his Ph.D. in 2000 from the Observatory of Neuchatel, Switzerland, for his thesis “Development of a Continuous Source of Laser-Cooled Cesium Atoms Applicable to Primary Reference Cesium Clock.” During the past 20 years, Patrick has gained considerable experience in time and frequency domain, in particular with the development of passive hydrogen masers for space applications (Galileo Navigation System), along with the development of magnetic and optically pumped cesium beam clocks for industrial applications. In 2008, he joined the Oscilloquartz Switzerland team, developing cesium beam clocks for telecom, navigation, and metrology applications. His current position is chief scientist of time and frequency at Oscilloquartz.