Chip Scale Atomic Clocks Sources

Future developments

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Agenda

1. Motivations for Next Generation CSACs
2. Proposed solutions
3. Conclusion

Motivations for Next Generation CSACs

Limitations of current CSACs

Current CSACs struggle to have short-term stability $\sigma_y(\tau) < 10^{-11}$ and long-term stability comparable with the one of CBT[1] clocks.

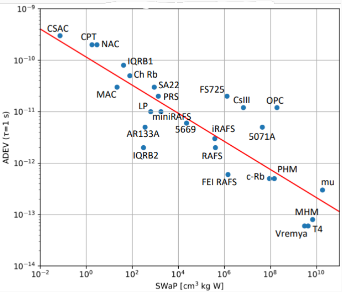


Figure 1: Allan deviation vs. Size, Weight and Power of different atomic clocks.

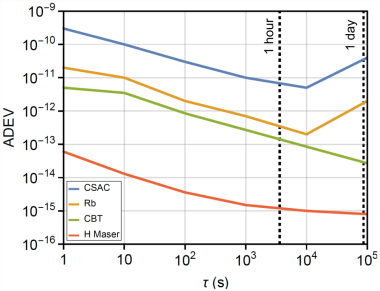


Figure 2: Short and medium term stability of different atomic clocks.

Next generation of CSACs (NG-CSACs) has to exploit different physics.

[1]CBT: Cesium Beam Tube

DARPA IMPACT & ACES programs

DARPA[1] is again the main driver for the development of NG-CSACs.

Funded projects include:

- IMPACT[2]: $20cm^3$, $250mW$ with $\sigma_y(\tau = 1month) < 160ns$.
- ACES[3]: palm sized, battery powered with $1000x$ performance improvements.
- ROCkN[4]: continuing of the ACES program.

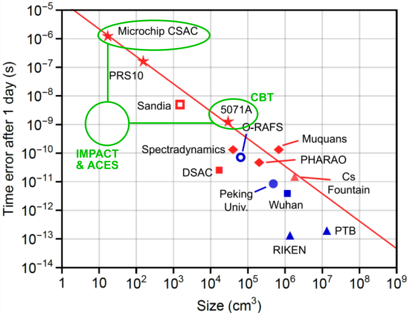


Figure 3: Programs' stability targets.

[1]DARPA: Defense Advanced Research Projects Agency.
[2]IMPACT: Integrated Miniature Primary Atomic Clock Technology (2009-2015).
[3]ACES: Atomic Clock with Enhanced Stability (2015-2022).
[4]ROCkN: Robust Optical Clock Network (2022-ongoing).

Proposed solutions

Proposed solutions

One of the most evident cause of instability and inaccuracy in CSACs is the Doppler broadening of the atomic transitions and the collisional shifts happening in the reference cell.

To reduce these effect and improving clock performances, three possible solutions are being investigated:

- Microwave transitions in a laser-cooled alkali metals
- Microwave transitions in double-resonance trapped ions
- Optical transitions in warm atomic/molecular vapors

Microwave transitions in laser-cooled alkali metals

Atoms cooling is a common technique used to **mitigate the Doppler broadening** of the atomic transitions and **reduce the collisional shifts**.

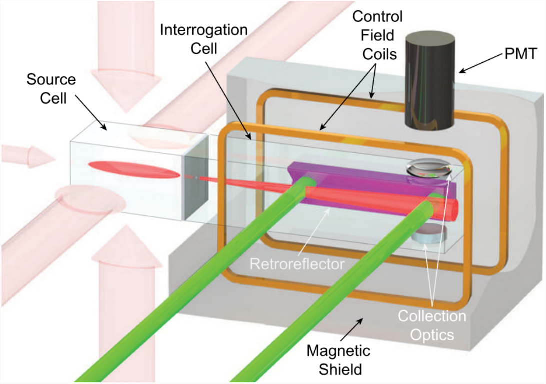


Figure 4: Schematic of a 2D-MOT[1] and the interrogation cell.

[1] 2D-MOT: 2D Magneto-Optical Trap

Current results

Stability results look promising but as of today the main bottlenecks are given by the **technological and experimental limitations**. A consistent advancement in those areas is needed to make this technology a viable solution for the future.

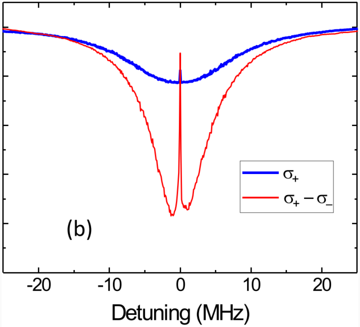


Figure 5: Laser-cooled vs. traditional CSAC transmission.

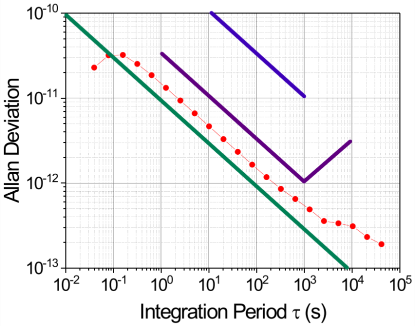
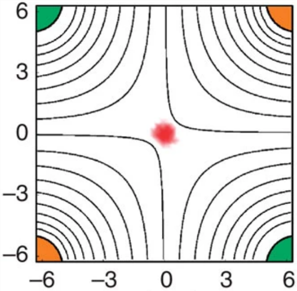


Figure 6: Target, SA.55 MAC, SA.45s CSAC, Laser-cooled CSAC

Microwave transitions in double-resonance trapped ions

Working principle

The working principle is very similar to the one of the laser-cooled alkali metals, but with the **use of ions instead of atoms and a different cooling mechanism**.



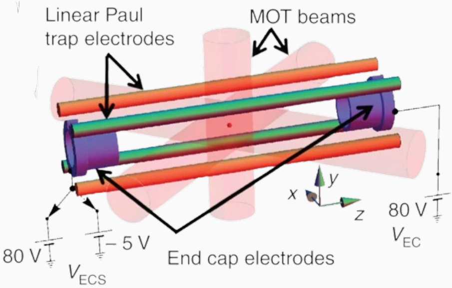


Figure 7: Schematic of the ion trapping setup (Paul trap).

The strong reduction of the Doppler broadening and the possibility of miniaturization makes this approach the most favorable for the NG-CSACs.

Ytterbium based clock

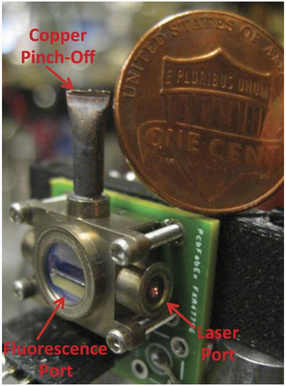


Figure 8: Ion trap and vacuum package ($\approx 0.8cm^3$).

One example of this technology is the $^{171}Yb^{+}$-based clock, **developed by Sandia and JPL (2015)**.

Known challenges and complications to achieve higher performances are:

- Stark Shift effect: pulsed laser interrogation is required to avoid a shift in the ions transition frequency.
- Long life state $^{2}F_{7/2}$: the ions can fall into a long life state, from which must be released used an additional laser source or buffer gas.

Mercury based clock

Another example is the $^{199}Hg^{+}$-based clock, **developed by JPL (2019)** as a miniaturization of the current Deep Space Atomic Clock (DSAC).

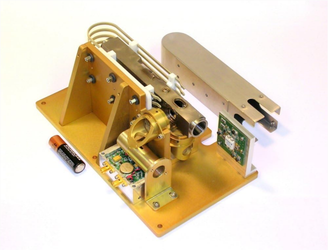


Figure 9: Physics package ($\approx 3dm^3$).

Born as a demonstration of the feasibility for a miniaturized version of the current DSAC with enhanced performances.

Its technology can be well suited adopted for a miniaturized version (NG-CSAC).

Current results

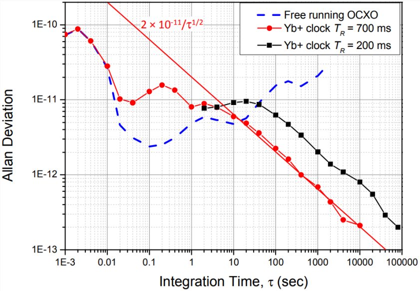


Figure 10: Sandia clock performances[1].

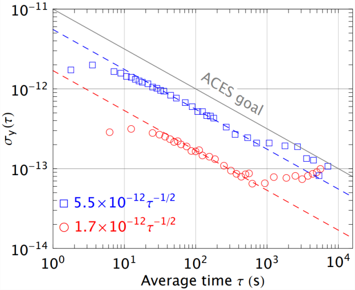


Figure 11: JPL clock performances[1].

Trapped ions is probably the most promising solution for the NG-CSACs.

Further development is required to mitigate instabilities (Stark Shift effect) and reduce system complexity (pulsed laser interrogation).

[1]Performances are comparable recalling the different size of the two systems.

Optical transitions in warm atomic/molecular vapors

Working principle

Large scale optical transitions clocks has already shown a short-term stability $\sigma_y(\tau = 1s) \approx 10^{-18}$. Here, **quartz crystal local oscillator is replaced by a laser tuned to an atomic transition**.

Two different physics are exploited to reduce the Doppler broadening:

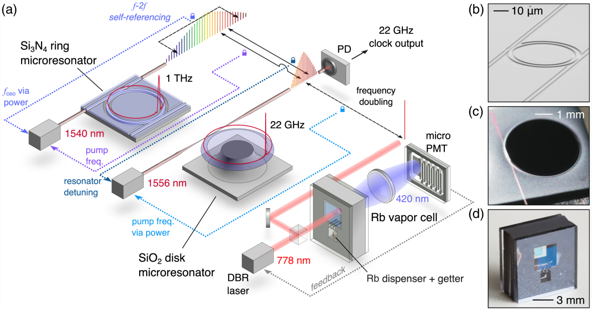
- MTS[1]: nonlinear interaction of laser light with atoms allows the use of a dual laser system to enable sub-Doppler spectroscopy.
- TPS[2]: shift in frequency due to moving atoms are suppressed by using two laser waves travelling in opposite directions.

[1]MTS: Modulation transfer spectroscopy
[2]TPS: Two-photon transitions

Two-photon transitions based clocks

So far, just a few optical-CSACs have been developed (experimental stage) all exploiting TPS.

NIST Chip-Scale Optical Atomic Clock (2019).

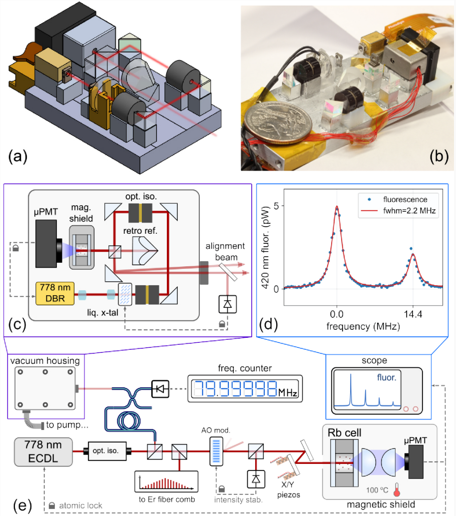


Critical components:

- DBR lasers
- Kerr-micro-resonator frequency combs
- Waveguides

The **miniaturization of all the required components is the main challenge** in the optics of the NG-CSACs.

Two-photon transitions based clocks



NIST & DRAPER optical-MAC[1] (2020).

Critical components:

- Microfabricated photomultiplier tubes
- DBR lasers
- Micro optics breadboards components

[1] MAC: Miniature Atomic Clock

Current results

Stability result shows that CSAC exploiting optical transitions met the DARPA ACES program requirements (shown in red in the figures below).

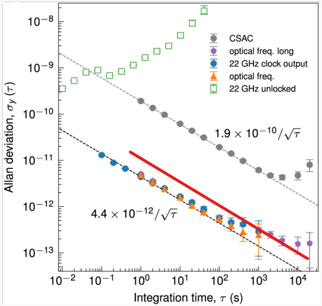


Figure 12: NIST optical-CSAC stability.

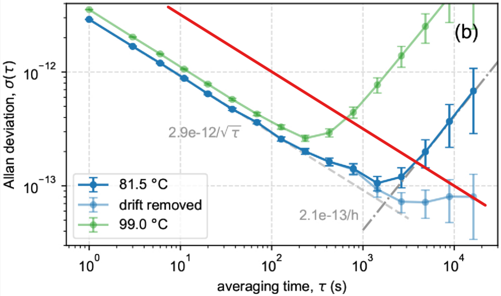


Figure 13: NIST & DRAPER optical-MAC stability.

However, **the development of integrated custom micro components**, such as fast-frequency-tunable lasers and frequency microcombs, **is still a challenge**.

Conclusion

Current research status for NG-CSACs

Despite more than 15 years since the launch of the first program to develop the NG-CSACs, many challenges remain to be addressed.

Three possible technological solution have been proposed, but a clear winner hasn't emerged yet.

Potential and Importance of NG-CSACs

In conclusion, we believe that pursuing the development goals set for NG-CSACs is extremely important.

These devices will not only provide superior timing and synchronization, but they also hold the **potential to bring revolutionary advances in areas like micro and nano fabrication, quantum computing, or the understanding of fundamental physics phenomena**.

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Questions?

Thank you!