



HAL
open science

Progress on a 171 Yb-Based Active Optical Atomic Clock

F. Ponciano-Ojeda, J. El Badawi, M. Hauden, M. Matusko, Marion Delehay

► **To cite this version:**

F. Ponciano-Ojeda, J. El Badawi, M. Hauden, M. Matusko, Marion Delehay. Progress on a 171 Yb-Based Active Optical Atomic Clock. 2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), May 2023, Toyama, Japan. pp.1-2, 10.1109/EFTF/IFCS57587.2023.10272180 . hal-04727400

HAL Id: hal-04727400

<https://hal.science/hal-04727400v1>

Submitted on 10 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Progress on a ^{171}Yb -Based Active Optical Atomic Clock

F. S. Ponciano-Ojeda, J. El Badawi, M. Hauden, M. Matusko, M. Delehaye

Time & Frequency Department
FEMTO-ST, CNRS/ENSMM/UBFC
Besançon, France
francisco.ponciano@femto-st.fr

Summary — We present our progress on the construction of a ^{171}Yb -based active optical atomic clock. The ytterbium (Yb) atoms, initially in a collimated thermal beam generated in an oven, are decelerated using a Zeeman slower to the capture velocity ($\sim 10 \text{ ms}^{-1}$) for a magneto-optical trap on the $^1\text{S}_0 \rightarrow ^3\text{P}_1$ transition at 556 nm. This allows us to generate an ensemble of $N > 10^6$ atoms at temperatures below $100 \mu\text{K}$, which will be transported using an optical conveyor belt to an ultra-stable ($\sigma_y \sim 10^{-13}$) cavity of finesse on the order of 10^4 . Here, the atoms will be prepared in order to generate a superradiant emission which will serve as the frequency reference on the $^1\text{S}_0 \rightarrow ^3\text{P}_0$ clock transition in ^{171}Yb .

Keywords — ytterbium; optical clock; cold atoms; superradiance

I. INTRODUCTION

The measurement and determination of time has been a key driver of the scientific and technological developments in society which has seen great advances in the past decades. The appearance of optical clocks, with fractional frequency instabilities at the seventeenth/eighteenth decimal [1-3], has started to usher in a new era of precision timekeeping that promises to bring further developments and discoveries. Nevertheless, the technical limitations for the operation of these ‘passive’ clocks – namely the instability and thermal noise in the high-finesse cavities used – are not easily overcome and have created opportunities for new clock designs to appear. A case of particular interest is that of using atomic transitions with narrow linewidths directly as an ultra-stable frequency reference rather than a conventional ultra-stable optical cavity for the clock laser, thus creating what has been called an ‘active’ optical clock [4]. Proposals for active optical clocks relying on the phenomenon of superradiance, where an ensemble of atoms undergoes a coherent and collective spontaneous emission, have attracted attention for being able to overcome some of the limitations of state-of-the-art passive clocks [5-7]. These proposals take advantage of the superradiant emission of the atoms to generate a signal, the optical power of which scales as the number of atoms squared (N^2); as the narrow linewidth clock transitions are usually weak, this scaling allows for useful optical power to be obtained directly from this transition. While not without limitations of their own, such as the challenge of achieving continuous superradiant emission, active optical clocks have the potential to become a new benchmark for precision

timekeeping. In this work we present the progress on the construction of a cold-atom-based active optical clock designed to take advantage of the superradiant emission on the spin- and dipole-forbidden $^1\text{S}_0 \rightarrow ^3\text{P}_0$ narrow-linewidth transition in fermionic 171-ytterbium (Yb). The goal of this project is to obtain a fractional frequency stability that is competitive with that of passive optical atomic clocks ($\sigma_y \sim 10^{-17}$) through the operation of a continuous superradiant laser emission from the atomic samples used.

II. METHODS/RESULTS

Our experimental setup consists of three main stages (see Fig. 1). The first stage is an Yb oven, closely following the design presented in ref. [8], which generates a collimated thermal beam of natural-abundance Yb for use in our experiments. This allows us to have a high flux of atoms in a slowly diverging beam that travels towards the second stage of our experiment, which is responsible for cooling the atoms. The thermal beam is first decelerated in a Zeeman slower (ZS) by using a counter-propagating beam 400 MHz red-detuned from the $^1\text{S}_0 \rightarrow ^1\text{P}_0$ transition ($\Gamma = 30 \text{ MHz}$) at 399 nm together with a spatially-varying magnetic field profile. In this way we manage to reduce the average velocity of a fraction of

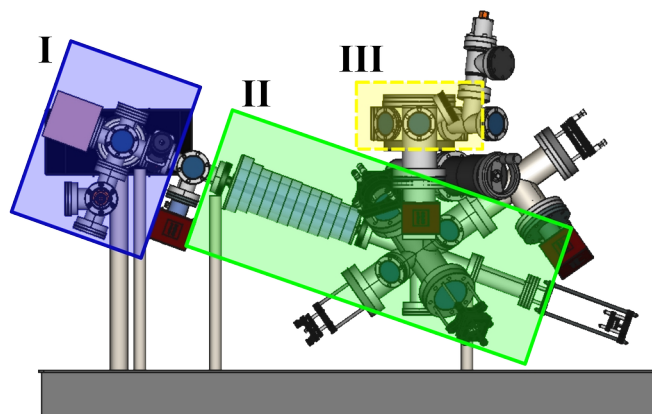


Fig. 1. Diagram of the experimental setup for our Yb-based active optical clock. The experiment is divided in three main stages: I) an oven that generates a thermal, collimated beam of natural-abundance Yb atoms, II) a cooling stage consisting of a Zeeman slower and a 3D magneto-optical trap and III) an ultra-stable cavity in which atoms will be held by a crossed dipole trap at 759 nm in order to generate superradiance to stabilize the clock laser.

the atoms from $\sim 400 \text{ ms}^{-1}$ at the input of the ZS to $\sim 10 \text{ ms}^{-1}$ at its output. At this final average velocity, the atoms can then be trapped in a standard three-dimensional magneto-optical trap (MOT) operating on the $^1S_0 \rightarrow ^3P_1$ transition ($\Gamma = 182 \text{ kHz}$), with a Doppler-limited temperature of $T_{\text{Dopp}} \sim 4 \text{ } \mu\text{K}$. Optimization of the magnetic field intensities used in both the ZS and MOT, the beam intensities and their detunings at this second stage gave us preliminary samples of approximately 10^6 atoms at temperatures lower than $100 \text{ } \mu\text{K}$. From here, the atoms will be transported using an optical conveyor belt over a distance of $\sim 40 \text{ cm}$ to the third stage of our experiment. This consists of an ultra-stable tunable cavity in which the atoms will be held using a dipole trap in order to be efficiently coupled to the mode of cavity. Once here, the atoms will be interrogated using the narrow linewidth $^1S_0 \rightarrow ^3P_0$ clock transition at 578 nm .

III. DISCUSSION

We have currently begun work on the third stage of our experimental setup, which consists of a high-finesse ($\sim 10^4$) ultra-stable cavity which will allow our cold atoms to be trapped in a crossed-beam dipole trap at the magic wavelength for Yb (759 nm). Once inside the cavity, the atoms will be coupled to the cavity mode and prepared to generate superradiant pulses on the narrow ($\Gamma = 7 \text{ mHz}$) $^1S_0 \rightarrow ^3P_0$ clock transition at 578 nm ; by working in the ‘bad-cavity’ regime these pulses can then couple out of the cavity and be used to stabilize the frequency of the clock laser. With this design, we expect the initial fractional frequency stability of the system to be on the order of 10^{-13} . Future improvements focusing on obtaining a **continuous** superradiant emission (*i.e.* a super-radiant laser) should allow us to increase the performance of our system to the 10^{-17} level, which is similar to the best passive optical clocks currently available. We

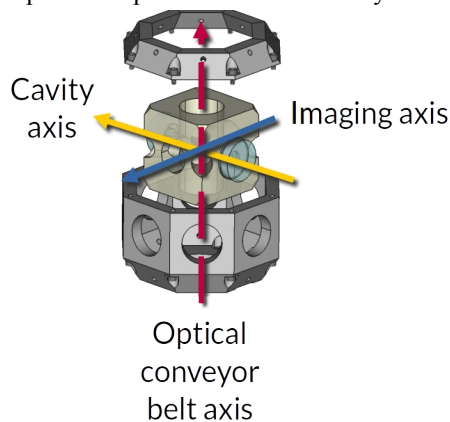


Fig. 2. Diagram of the ultra-stable cavity assembled for trapping and preparing Yb atoms for the generation of superradiant pulses. The cavity spacer is a 50 mm ULE tetrahedron inspired by the design proposed in ref. [9]. Optical access is present in all of the faces to allow for the beams needed for transporting atoms into the cavity, detecting them using a 399 nm imaging beam and for injecting the cavity with 578 nm light to subsequently probe the clock transition. On the edges of the spacer optical access is also necessary to generate the crossed-beam dipole trap that will hold the atoms inside the cavity.

envision this experiment to be a stepping stone on the path towards portable and commercially-feasible precision optical clocks.

IV. CONCLUSIONS

We present the experimental design and the progress made in the construction of an active optical clock based on superradiant emission of cold Yb atoms. Our experimental setup has produced preliminary samples of $\sim 10^6$ atoms at temperatures lower than $100 \text{ } \mu\text{K}$. Current work is focused on transporting these cold atoms into a high-finesse optical cavity, where they will be held with a crossed-beam dipole trap at the magic wavelength. By using the superradiant emission of these atoms to stabilize the frequency of the laser for the $^1S_0 \rightarrow ^3P_0$ narrow-linewidth clock transition, we expect a fractional frequency stability on the order of 10^{-13} . In the future, we plan to optimize the generation of the superradiant emission to create a continuous reference signal for our system which should allow us to reach fractional frequency stabilities that are competitive with the current generation of passive optical clocks.

REFERENCES

- [1] Schioppo, M., Brown, R., McGrew, W. *et al.* “Ultrastable optical clock with two cold-atom ensembles,” *Nature Photonics*, vol. **11**, pp. 48–52 January 2017. <https://doi.org/10.1038/nphoton.2016.231>
- [2] Boulder Atomic Clock Optical Network (BACON) Collaboration*. “Frequency ratio measurements at 18-digit accuracy using an optical clock network,” *Nature*, vol. **591**, pp. 564–569, March 2021. <https://doi.org/10.1038/s41586-021-03253-4>
- [3] McGrew, W.F., Zhang, X., Fasano, R.J. *et al.* “Atomic clock performance enabling geodesy below the centimetre level,” *Nature*, vol. **564**, pp. 87–90, December 2018. <https://doi.org/10.1038/s41586-018-0738-2>
- [4] Muniz, J.A., Cline, J.R.K., Norcia, M.A. and Thompson, J.K. “An active optical frequency reference using a pulsed superradiant laser”, *Proc. SPIE vol. 10934, Optical, Opto-Atomic, and Entanglement-Enhanced Precision Metrology*, 109342B, March 2019. <https://doi.org/10.1117/12.2515582>
- [5] Norcia, M.A., Cline, J.R.K., Muniz, J.A., Robinson, J.M., Hutson, R.B., Goban, A., Marti, G.E., Ye, J., and Thompson, J.K. “Frequency Measurements of Superradiance from the Strontium Clock Transition,” *Physical Review X* vol. **8**, no. 2, pp. 021036, May 2018. <https://doi.org/10.1103/PhysRevX.8.021036>
- [6] Norcia, M.A., Winchester, M.N., Cline, J.R.K., and Thompson, J.K. “Superradiance on the Millihertz Linewidth Strontium Clock Transition,” *Science Advances* vol. **2**, no. 10, pp. E1601231, October 2016. <https://doi.org/10.1126/sciadv.1601231>
- [7] Norcia, Matthew A. “Coupling Atoms to Cavities Using Narrow Linewidth Optical Transitions: Applications to Frequency Metrology.” *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. **52**, no. 19, pp. 193001, September 2019. <https://doi.org/10.1088/1361-6455/ab3930>.
- [8] Dureau, Alexandre. “Manipulation cohérente d’un condensat de Bose-Einstein d’ytterbium sur la transition “d’horloge”: de la spectroscopie au magnétisme artificiel.” *Ph.D. thesis*, Physique [physics], Ecole normale supérieure - ENS PARIS, 2015. Français. NNT:2015ENSU0018. tel-01194429v3
- [9] Webster, S. & Gill, P. “Force-insensitive optical cavity,” *Optics Letters* **36**, pp. 3572–3574, 2011. <https://doi.org/10.1364/OL.36.003572>