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 (~ 10 ms^{-1}) for a magneto-optical trap on the $^1S_0 \rightarrow {}^3P_1$ transition at 556 nm. This allows us to generate an ensemble of $N > 10^6$ atoms at temperatures below 100 μK, 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 $^1S_0 \rightarrow {}^3P_0$ clock transition in ^{171}Yb.**

***Keywords* — ytterbium; optical clock; cold atoms; super-radiance**

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 $^1S_0 \rightarrow {}^3P_0$ 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 $^1S_0 \rightarrow {}^1P_0$ transition (Γ = 30 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

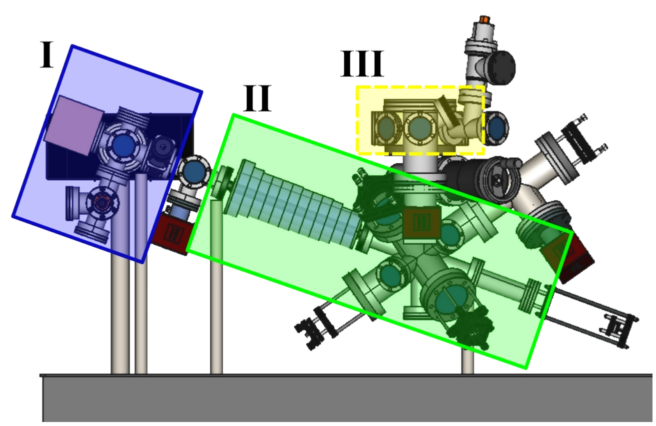

Fig. 1. Diagram of the experimental setup for our Yb-based active optical clock. The experiment is divided in three main stages: I) an oven that generates a thermal, collimated beam of natural-abundance Yb atoms, II) a cooling stage stage consisting of a Zeeman slower and a 3D magneto-optical trap and 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 ~ 400 ms^{-1} at the input of the ZS to ~ 10 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 (Γ = 182 kHz), with a Doppler-limited temperature of T_{Dopp} ~ 4 μK. 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 μK. From here, the atoms will be transported using an optical conveyor belt over a distance of ~ 40 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 (~ 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 (Γ = 7 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 envision this experiment to be a stepping stone on the path towards portable and commercially-feasible precision optical clocks.

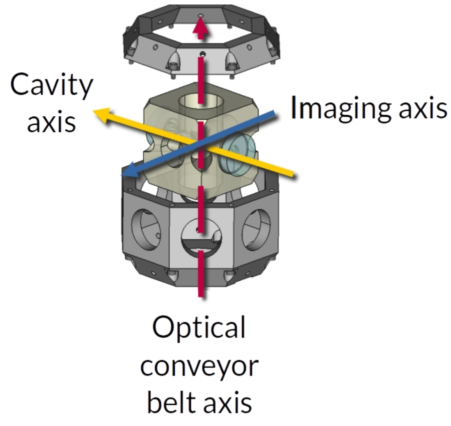

Fig. 2. Diagram of the ultra-stable cavity assembled for trapping and preparing Yb atoms for the generation of superradiant pulses. The cavity spacer is a 50 mm ULE tetrahedron inspired by the design proposed in ref. [9]. Optical access is present in all of the faces to allow for the beams needed for 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.

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 ~ 10^6 atoms at temperatures lower than 100 μK. 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.

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