Towards a Continuous Active Optical Atomic Clock With Cold Strontium Atoms

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***Abstract*—We present a setup designed for an active optical atomic clock operating at the clock transition (1S0-3P0) with cold strontium atoms. The apparatus is designed for continuous operation, and it is designed for both 87Sr and 88Sr isotopes.**

Keywords—active optical clock, strontium

I. Introduction

The superradiant [1] active clocks [2] should allow fully utilizing the extremely-narrow linewidth of clock transitions in alkaline-like atoms [3,4]. While the linewidth of the clock laser used in a standard passive optical clock is limited by the cavity thermal noise and mechanical vibrations [5], in an active superradiant clock the linewidth depends on the width of the ultra-narrow transition multiplied by the cooperativity parameter of the cavity [3]. Although the pulsed superradiant lasing of cold atoms in a cavity was observed lately experimentally [6-8] the continuous operation has not yet achieved.

The goal of this work is to report a setup that allows us to generate superradiant pulses on the clock transition with strontium atoms trapped in a lattice, and in the next step to sustain the continuous or quasi-continuous operation [9]. We designed a vacuum setup which consists of two regions with cavities for superradiance in each region. All relevant parameters are tested in a set of numerical calculations [10]. The setup includes in-vacuum magnetic coils in a magnetic shield, an isolated spacer for superradiance cavities and a system for trapping, cooling and transporting atoms in an optical lattice. The system will be subsequently connected to a continuous source of cold strontium atoms [11]. Fig. 1 presents in three steps a principle of operation.

II. Methods

The vacuum apparatus, presented in the Fig. 2 is designed to be versatile. It can host inside relatively large installations like a monolithic spacer for two superradiance cavities, magnetic field coils and magnetic shields. Excellent control over magnetic field is required, particularly for strontium 88. In this isotope the clock transition width can be magnetically tuned. Additionally for continuous operating of the clock we

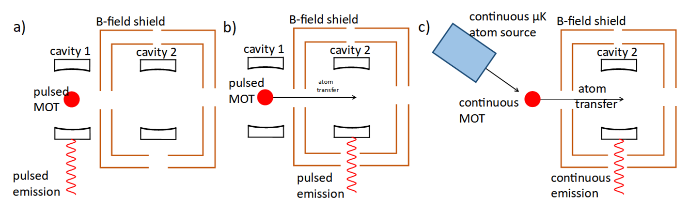

Fig. 1. Three steps of experiment: a) superradiance pulses from conventional hot Sr source, b) testing atom transfer to the cavity 2 and pulses form controlled environment in magnetic shield, c) conventional Sr source replaced with continuous source (atoms at a few uK), continuous loading to cavity 2 and continuous superradiance.

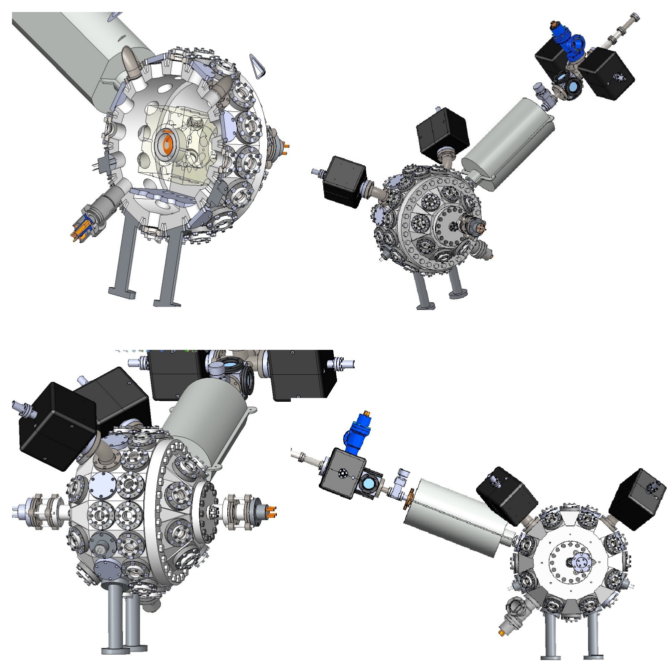

Fig. 2. Vacuum setup. The overview is presented together with a cross-section of the main chamber. A standard Zeeman slower (inside magnetic shield) and an oven will be used in first stage.

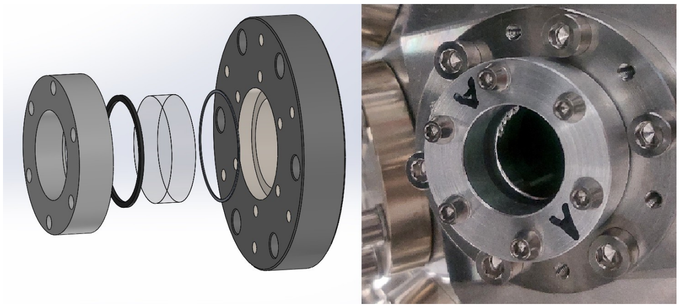

Fig. 3. Viewports made of titanium flanges with glass windows sealed with an indium wire. A Viton gasket is placed between glass and an aluminum ring that presses the window.

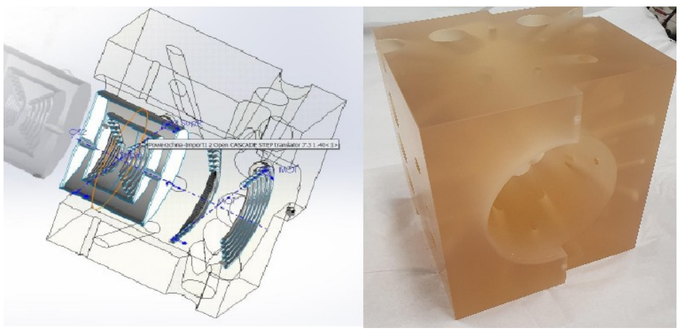

Fig. 4. A Zerodur spacer for two superriadiance cavities. On the left the position of the magnetic coils is presented and on the right a photo of the Zerodur spacer is shown.

need to isolate both magnetically and optically the superradiance area from the cold atom reservoir where atoms will be prepared.

The main chamber is made of titanium which has excellent magnetic properties and good vacuum compatibility. The only few stainless steel elements will be located more than 16 cm from the chamber centre. The vacuum viewports presented in Fig. 3 are made of titanium, aluminum, and glass are sealed with indium wire. In this way we avoid using magnetic nickel–cobalt ferrous alloys, which are typically used in standard viewports. All elements inside and close to the main chamber will be non-magnetic, which will allow us to precise control the magnetic field. Compensation coils will be placed outside the chamber. Ion pumps will be installed on flexible connections and can be further distanced from the chamber. All pumps will be placed inside magnetic shields.

For the precise control of the magnetic field inside the chamber two pairs of magnetic coils will be installed inside the vacuum setup. Both pairs will be placed inside a Zerodur spacer of the superradiance cavity (see Fig. 4). There will be no contact between spacer and coils to isolate vibration from water cooled coils. Positioning of both pair of coils will be possible from outside. One pair of coils will be installed in a magnetic shield, presented in Fig. 5. Simulated magnetic field (Fig. 6) predicts an excellent control over the area where atoms will be placed inside the superradiance cavity.

In the first stage the strontium atoms will be loaded form a standard oven and a Zeeman slower [12]. In this way the strontium atoms will be provided for testing and the first

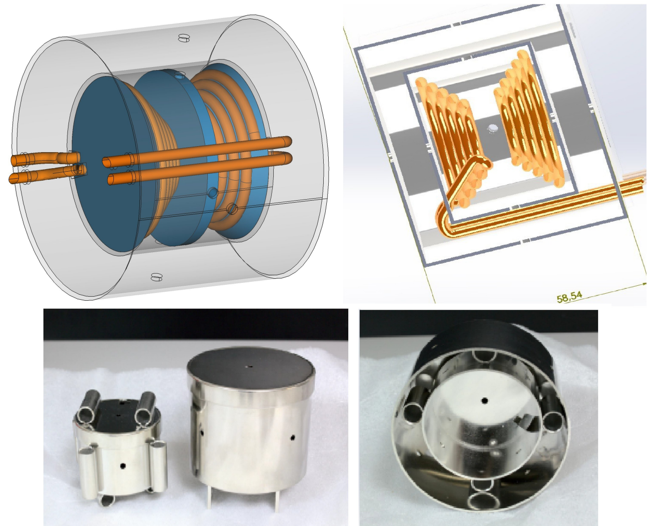

Fig. 5. The magnetic field coils inside a two-layer magnetic shield: a cross section of the design (top) and an actual photo (bottom). The shield is made of mu-metal.

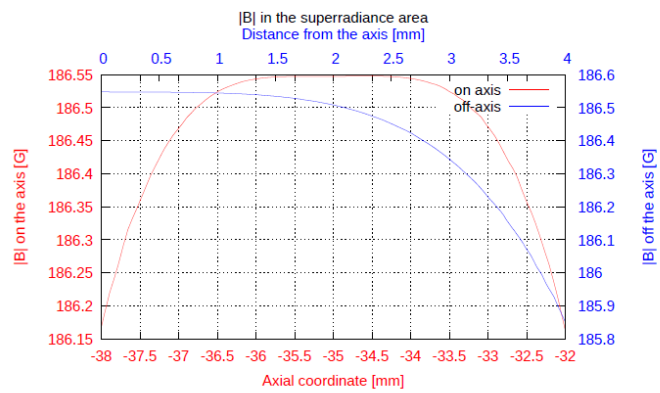

Fig. 6. Magnetic field strength and distribution in the centre of magnetic shield.

superiadiance pulse generation. The setup allows combining it with the continuous source of cold strontium atoms reported recently [11].

III. Conclusions

We preseted a vacuum setup for continous superradiance clock. We concentrated on the control of the magnetic field. The setup will be tested in a pulse operation and later it will sustain the continous operation.

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References

[1] R H Dicke, “Coherence in Spontaneous Radiation Processes,” Phys. Rev. 93 pp 99–110 January 1954

[2] J Chen, “Active optical clock,” Chin. Sci. Bull. 54 pp 348–352 February 2009

[3] D Meiser, J. Ye, D. R. Carlson, and M. J. Holland, “Prospects for a Millihertz-Linewidth Laser,” Phys. Rev. Lett. 102 pp 163601 April 2009

[4] D Yu and J Chen, “Laser theory with finite atom-field interacting time,” Phys. Rev. A 78 pp 013846 July 2008

[5] K Numata, A. Kemery, and J. Camp, “Thermal-Noise Limit in the Frequency Stabilization of Lasers with Rigid Cavities,” Phys. Rev. Lett. 93 pp 250602 December 2004

[6] M A Norcia, M N Winchester, J R K Cline and J K Thompson, “Superradiance on the millihertz linewidth strontium clock transition,” Sci. Adv. 2 pp e1601231 October 2016

[7] T Laske, H Winter, and A Hemmerich, “Pulse Delay Time Statistics in a Superradiant Laser with Calcium Atoms,” Phys. Rev. Lett. 123 pp 103601 September 2019

[8] S A Schäffer, et al., “Lasing on a narrow transition in a cold thermal strontium ensemble,” Phys. Rev. A 101 pp 013819 January 2012

[9] G A Kazakov and T Schumm, “Active optical frequency standard using sequential coupling of atomic ensembles,” Phys. Rev. A 87 pp 13821 January 2013

[10] A Gogyan, G Kazakov, M Bober and M Zawada, “Characterisation and feasibility study for superradiant lasing in 40Ca atoms,” Opt. Express 28 pp 6881-6892 2020

[11] C Chen, S Bennetts, R G Escudero, B Pasquiou and F Schreck, “Continuous Guided Strontium Beam with High Phase-Space Density,” Phys. Rev. Appl. 12 pp 044014 October 2019

[12] M Bober, J Zachorowski and W Gawlik, “Designing Zeeman slower for strontium atoms - towards optical atomic clock,” Opt. Appl. 40 pp 547-555 2010