PROGRESS TOWARDS A STRONTIUM OPTICAL LATTICE CLOCK AT NPL

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INTRODUCTION

The $^1S_0 - {}^3P_0$ transition at 698 nm in neutral strontium has the potential to be an extremely precise optical frequency standard [1] and is one of several candidates for a future redefinition of the second. Recent measurements of this transition at three national laboratories around the world have fractional frequency uncertainties in the 10^{-15} range and agree to within a hertz [2,3,4]. To realise fully the potential accuracy of this frequency standard, in-depth studies of systematic effects need to be performed in order to characterise them at the level necessary for a redefinition of the second. At the National Physical Laboratory we are developing a compact, diode-laser-based optical lattice clock. We intend to study the clock transition in both ^{88}Sr and ^{87}Sr with focus on the uncertainties in the frequency shifts due to blackbody radiation. The setup incorporates a novel permanent-magnet-based Zeeman slower [5].

EXPERIMENTAL SYSTEM

Vacuum Apparatus

We are designing an experimental system with a compact footprint. Our main vacuum chamber measures just over 1 m in length, half that in width, and less than 30 cm at its tallest point. It includes an oven, a Zeeman slower, a 2D transfer MOT chamber, and a final small-scale lattice chamber in which the clock transition will be measured (see Fig. 1). The oven consists of a heater-wire-wrapped crucible to hold the strontium and a microchannel nozzle to help collimate the thermal atomic beam. Both can be heated to > 600 °C, and the nozzle is kept hotter than the crucible at all times to avoid blockages.

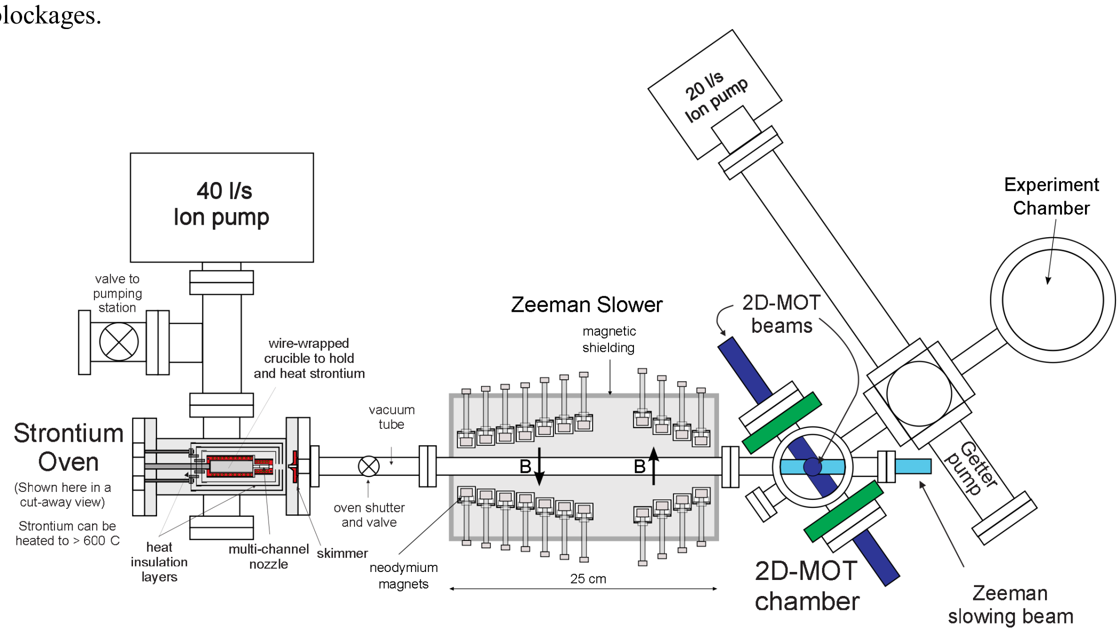

Fig. 1. Experimental layout of the compact vacuum system for the strontium lattice clock.

First-Stage Cooling Transition

Strontium has a broad transition (linewidth of $2\pi \times 32$ MHz) between the $^1S_0 - {}^1P_1$ states at 461 nm, which is ideal for first-stage cooling of the atoms, and has a Doppler cooling limit of 0.8 mK. We use a frequency doubled MOPA diode laser system (Toptica's TA-SHG) to produce up to 400 mW of 461 nm light. The laser frequency is stabilized by locking its IR diode output to a scannable, low-drift Fabry-Perot cavity. This light will be used for decelerating the atoms with the Zeeman slower, transferring them out of the atomic beam path to the experiment chamber with the 2D-MOT, and further confining and cooling them in a 3D-MOT.

Permanent Magnet Zeeman Slower

Experiments involving strontium usually rely on a Zeeman-slowed atomic beam to load a magneto-optical trap (MOT) as a first stage of cooling and confinement before transferring these atoms into the lattice trap. One key innovation in the miniaturization of our system is the development of a novel type of Zeeman slower based on permanent magnets [5], as shown in Fig. 2. By using permanent magnets rather than current-carrying coils as a source for the Zeeman slower's transverse magnetic field, we eliminate the need for (and noise from) power supplies and water cooling. Additionally, the Zeeman slower can be removed from the vacuum system for adjustment without breaking vacuum and its field can be fine-tuned *in situ*.

We are currently measuring and optimising the performance of our Zeeman slower by scanning a 461 nm probe laser over the atomic velocity distribution. A slow atom peak at ~50 m/s has been observed, but further adjustments are required to reduce this to the desired 25 m/s. We have demonstrated first-stage cooling by trapping atoms in a 3D-MOT using the 461 nm transition.

Second-Stage Cooling Transition

The spin-forbidden $^1S_0 - {}^3P_1$ transition at 689 nm is used for second-stage cooling. A Littrow-configured extended cavity (L = 10 cm) diode laser produces ~10 mW of light at 689 nm. This is locked to a high finesse (130,000) cylindrical ULE cavity via the Pound-Drever-Hall technique with fast and slow feedback to the diode current and diffraction grating piezo respectively. Measurements indicate a locked laser linewidth of around 5 kHz, less than the linewidth of the transition (7 kHz). The drift of the locked laser is less than 3 Hz/s; this can be corrected for by the AOM used to bridge the frequency gap between the optical cavity mode and the atom resonance.

Lattice Laser

We will use a red-detuned 1D vertical lattice at the magic wavelength of ~813 nm to trap the atoms for probing of the clock transition. The lattice laser will consist of an ECDL in Littrow configuration plus tapered amplifier, with the master diode stabilised to a ULE spacer optical cavity of finesse ~3000. To aid tuning of the system, the standard Littrow configuration ECDL is modified to include a beam-steering compensation mirror, which tracks the diffraction grating angle producing just a small lateral displacement of the beam over a range of wavelengths [6]. We expect to deliver up to 300 mW to the experiment via an optical fibre.

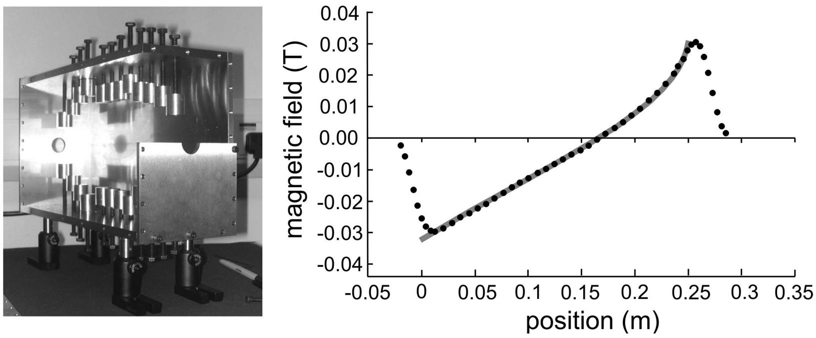

Fig. 2. Picture of Zeeman slower and plot of magnetic field along the axis of the slower.
(Theoretical calculation shown by solid line overlaid with measurements from Zeeman slower.)

Clock Laser System

In order to probe the narrow (few millihertz) linewidth clock transition with high resolution, a laser with sub-hertz linewidth is desirable. We have two identical, independent probe laser systems at 698 nm under development. This will enable us to determine laser linewidth via beat note detection. Each laser system consists of an ECDL at 698 nm stabilised to a high-finesse, vibrationally insensitive, ULE Fabry-Perot cavity [7]. The cavities are mounted vertically, supported by three Teflon rods held in a ULE ring, which is supported by three Viton balls, as shown in Fig. 3. The vacuum chambers are made from aluminium, possessing a high coefficient of thermal conductivity, which facilitates high stability and uniformity of the cavity temperature. The chambers have an additional inner heat shield providing a second layer of temperature stabilisation. The temperature of the inner shield has been stabilised to a few hundred micro-kelvin via PID control of thermoelectric coolers. Each cavity will be temperature stabilised at its point of zero thermal expansion, ~10 °C. The lasers, optics and cavities are mounted on active vibration isolation platforms on the floor of an acoustically isolated, temperature stabilised room.

Blackbody Radiation Shift Measurement

One of the largest systematic uncertainties when measuring the frequency of the strontium clock transition is that due to the limited knowledge and control of the frequency shift due to blackbody radiation. Theoretical calculations estimate this frequency shift, $\delta\nu$, in Hz as:

$$\delta\nu = -2.354(32) \times \left(\frac{T}{300}\right)^4 \quad (1)$$

Where T is the temperature in kelvin [8]. The theoretical coefficient in equation (1) is yet to be verified experimentally and subsequently contributes largely to the uncertainty budget for the frequency measurement. Until this shift is well characterised it can be reduced by cooling the experiment chamber, but this introduces additional technical challenges. At NPL we plan to measure this frequency shift over a range of elevated temperatures, experimentally verifying the coefficient in equation (1) and reducing its uncertainty. We will change the temperature of the environment by over 100 K, which should give a frequency shift of ~10 Hz.

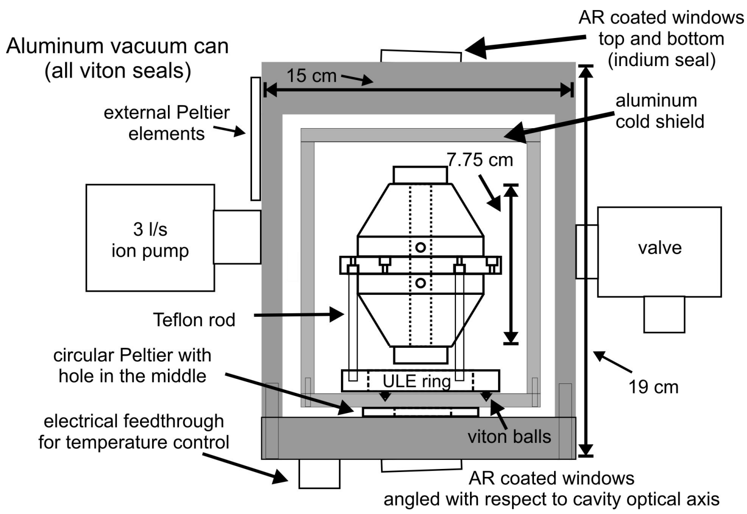

Fig. 3. Schematic of clock laser optical cavity mounted in vacuum chamber and inner heat shield.

ACKNOWLEDGEMENTS

This work was supported by the UK Department of Business, Innovation and Skills as part of the National Measurement System Pathfinder Metrology and EU EMRP programmes. EMB acknowledges support from the UK Engineering and Physical Sciences Research Council.

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