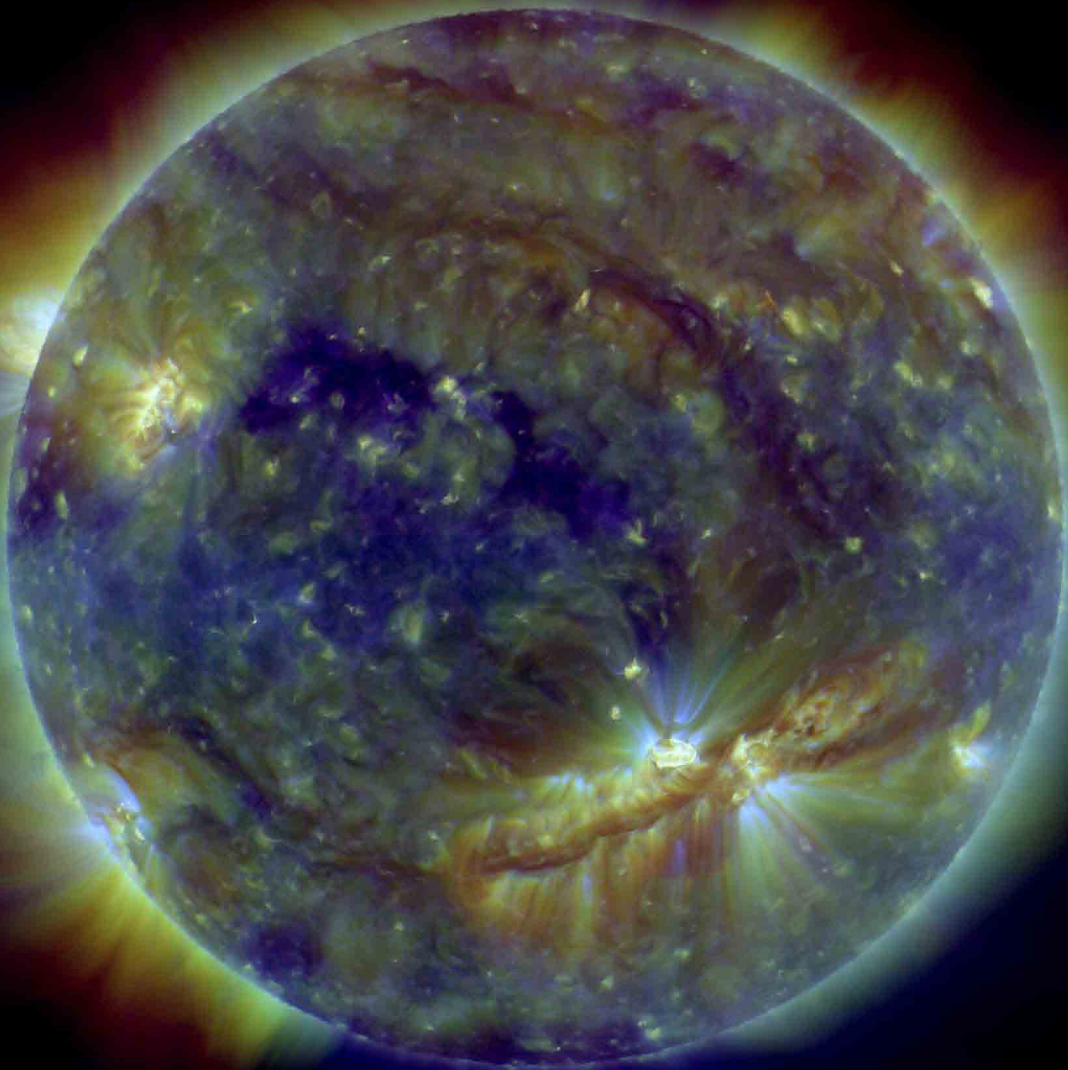




Let's embrace space

Volume II



*Enterprise and
Industry*

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EUROPEAN COMMISSION

Let's Embrace Space

Volume II

Directorate-General for Enterprise and Industry

Towards Neutral-atom Space Optical Clocks (SOC2): Development of high-performance transportable and breadboard optical clocks and advanced subsystems

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ABSTRACT

The use of ultra-precise optical clocks in space ('master clocks') will allow for a range of new applications covering the fields of fundamental physics (tests of Einstein's theory of General Relativity, time and frequency metrology by means of the comparison of distant terrestrial clocks), geophysics (mapping of the gravitational potential of Earth), and astronomy (providing local oscillators for radio ranging and interferometry in space).

Within the ELIPS-3 programme of ESA, the 'Space Optical Clocks' (SOC) project aims to install and to operate an optical lattice clock on the International Space Station (ISS) towards the end of this decade, as a natural follow-on to the Atomic Clock Ensemble in Space (ACES) mission (which is based on a cesium microwave clock), improving its performance by at least one order of magnitude.

The payload is planned to include an optical lattice clock, as well as a frequency comb, a microwave link, and an optical link for comparisons of the ISS clock with ground clocks located in several countries and continents.

Undertaking a necessary step towards optical clocks in space, the EU-FP7-SPACE-2010-1 project no 263500 (SOC2) (2011–15) will develop two ‘engineering confidence’, accurate transportable lattice optical clock demonstrators having relative frequency instability below 1×10^{-15} at 1 s integration time and relative inaccuracy below 5×10^{-17} . This goal performance is about 2 and 1 orders better in instability and inaccuracy, respectively, than today’s best transportable clocks. The devices will be based on trapped neutral ytterbium and strontium atoms. One device will be a breadboard. The two systems will be validated in laboratory environments and their performance will be established by comparison with laboratory optical clocks and primary frequency standards.

In order to achieve the goals, SOC2 will develop the necessary laser systems — adapted in terms of power, linewidth, frequency stability, long-term reliability, and accuracy. Novel solutions with reduced space, power and mass requirements will be implemented. Some of the laser systems will be developed towards particularly high compactness and robustness levels. Also, the project will validate crucial laser components in relevant environments. This paper will give an overview of the project and of the results achieved during the first year.

INTRODUCTION

The principle of an optical lattice clock is shown in Figure 1. A laser interrogates an ensemble of ultra-cold atoms, by exciting them to a long-lived atomic state via the clock transition. The atoms are trapped inside

a standing-wave laser field (‘optical lattice’) and possess a temperature of a few micro-Kelvin. The interrogation results in a signal proportional to the absorption of the laser light, which depends on the laser frequency ν . The signal is maximum when the laser frequency coincides with the centre of the atomic resonance ν_0 . With a feedback control, the laser frequency ν is continuously kept tuned on ν_0 . The resulting ultra-stable laser optical frequency ν_0 can be converted to an equally stable radio-frequency by means of a frequency comb.

The implementation of a lattice clock is shown in Figure 1, top right. An atomic beam produced by an oven travels towards the right through a spatially varying magnetic field. In it, the atoms are slowed down by a laser beam (blue arrow, from laser subsystem BB 1, see Figure 1 bottom) that finally nearly stops and traps the atoms inside the experimental chamber (square), in the 1st stage of a magneto-optical trap (MOT). Subsequently, they are cooled further to a lower temperature of a few tens of micro-Kelvin in a 2nd MOT stage by another laser subsystem (BB 2). In a third step, they are then transferred to an ‘optical lattice’ made of counter-propagating laser waves generated by a third laser subsystem (BB 4). Since the lattice potential ‘wells’ are deeper than the thermal energy of the atoms, they are trapped in the potential minima. There, the atoms are localised spatially in one dimension to well below one wavelength of the clock laser (BB 5) and this condition leads to an excitation spectrum free of 1st order Doppler spectral broadening or shift. Perturbing effects of the lattice light field on the atomic energy levels of the clock transition are minimised

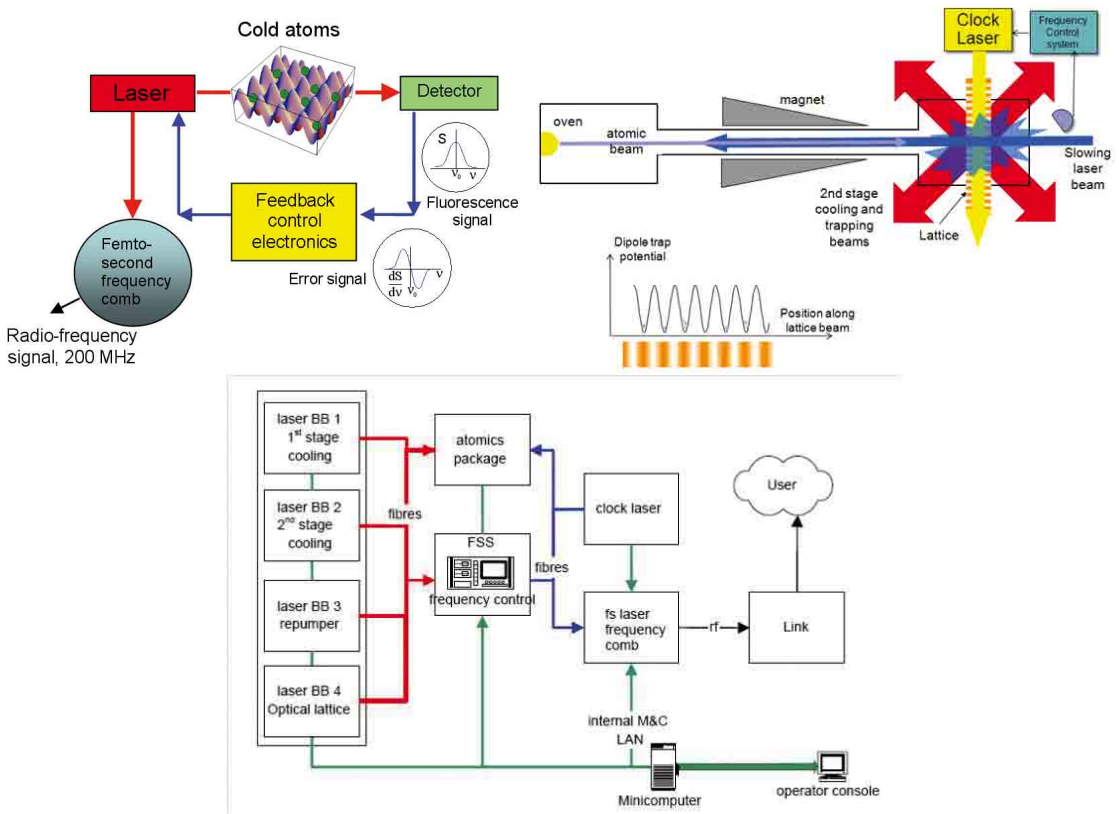


Figure 1. Top left, principle of an optical atomic clock based on atoms trapped by laser light. Top right, schematic of a lattice clock apparatus. Red: laser beams for 2nd stage cooling and trapping in the MOT. Orange-red: lattice laser standing wave; yellow: clock laser wave. Inset: variation of the potential felt by the atoms due to the lattice laser. Bottom, subsystems of a lattice optical clock.

by choosing a so-called ‘magic’ wavelength [Katori 2003, Porsev 2004]. The clock transition excitation is performed by the clock laser (BB 5). The laser subsystem BB 3 furnishes auxiliary laser light.

The subsystems of a lattice clock are shown in Figure 1 bottom. The laser light produced by the laser breadboards is transported via optical fibers to diagnostic and frequency stabilisation units, to the frequency comb, and to the vacuum chamber containing the atoms.

The work of this project involves developing all subsystems, in part in form of compact breadboards, and to integrate them into two transportable

clocks, one operating with strontium (Sr), the other with ytterbium (Yb). ^{87}Sr and ^{171}Yb are currently considered as the most promising isotopes.

ACHIEVED RESULTS

Laser system for Strontium clock

The design of the laser system for the Sr lattice clock is modular, and all modules are connected by optical fibers to the vacuum apparatus. This choice ensures high stability and reliability needed for long-term operation of a clock. Moreover, the modular approach allows for independent testing of the subcomponents and, during

the course of the project, simple replacement of components by more advanced components. The developments in the field of commercial lasers have produced impressive improvements in size, mass, stability and reliability of lasers and other optoelectronic components. The result is that the complete laser system for the Sr lattice optical clocks is based on off-the-shelf commercial components of moderate size and high reliability, such as diode lasers. The specifications are given in Table 1.

Based on ruggedised commercial systems, the lasers (TOPTICA) have been

integrated into compact subsystems where several output beams, controlled in amplitude and frequency via acousto-optical modulators, are produced: a main output to the atomics package, an output for the laser frequency stabilisation subsystem, and other additional service outputs. All outputs are provided in single-mode, polarisation-maintaining fibers.

The following laser sources have been developed and have been integrated with the atomic package (see Sec. 3): a frequency doubled diode laser (461nm) for 1st cooling (BB 1), a high-power 813 nm

Laser Breadboard	Wavelength	Frequency stability	Size in cm ³ , mass	Power at fiber outputs
BB 1: Cooling #1	461 nm ECDL+SHG	1 MHz	60×45×10 20 kg	140 mW to distribution breadboard
BB 1: Cooling #1 distribution	461 nm	1 MHz	30×45×10 12 kg	50 mW MOT, 30 mW slower, 1 mW selection, 1 mW (IR) FSS
BB 2: cooling #2	689 nm ECDL	< 1 kHz in 1 h, linewidth < 1 kHz with additional FM	60×45×12 20 kg	10 mW MOT , 1 mW FSS 1 mW to stirring breadboard
BB 2: Stirring and spin polarisation	689 nm ECDL	Offset-phase-locked to 689 nm cooling	30×45×10	10 mW MOT, 2×1 mW spin polarization
BB 3: Repumper	707 nm, 679 nm ECDL	FM +/- 3 GHz with a few kHz modulation frequency; center: 100 MHz	30×45×10, 12 kg	2 mW each wavelength to MOT, 1 mW to FSS
BB 4: Lattice	813 nm ECDL	< 10 MHz in 10 h	30×45×10 12 kg	>200 mW to atomics, 1 mW to FSS
BB 5: Clock laser	698 nm ECDL	<1 Hz	60×45×12 20 kg	2 mW to atomics, 2 mW to comb, 0.5 mW to cavity, 1 mW to FSS
BB 5: Clock cavity	698 nm	thermal noise 5×10 ⁻¹⁶	55×55×55, 30 kg	
FSS: Frequency stabilization system	all, excluding 698 nm	to levels indicated above	30×20×10, 10 kg	fiber input for the above fiber outputs

Table 1. Detailed specifications of the laser and stabilisation subsystems for the Sr clock.

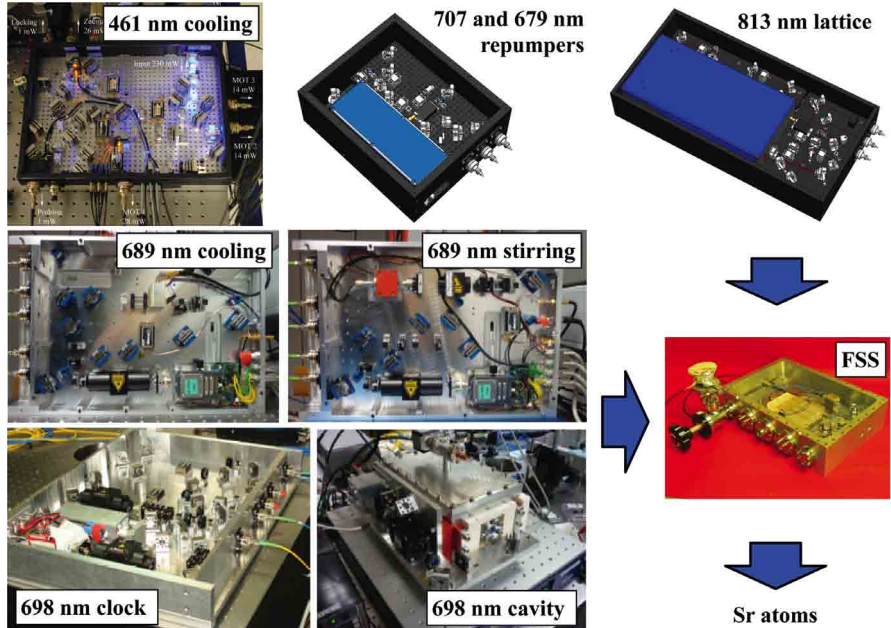


Figure 2: Overview of the laser subsystems for the strontium lattice clock, comprising seven lasers and the respective frequency stabilisation units (698 nm cavity of BB 5 and FSS).

Figure 2 shows the Sr laser subsystems assembled during the first year of the project. Together, they occupy a volume of ca. 300 litre with an approximate power consumption of 100 W and 150 kg mass.

laser for the dipole lattice trap (BB 4), two repumper lasers at 679 nm and 707 nm (BB 3). In addition, the highly frequency-stable 689 nm laser for 2nd stage cooling on the intercombination transition (BB 2) and the clock laser at 698 nm for the spectroscopy of the clock transition will soon also be integrated.

Laser system for the Ytterbium clock

For the operation of an Yb optical lattice clock, lasers with five different wavelengths are required. In the project, we develop compact and transportable laser sources based on state-of-the-art diode and fiber laser technology, see Figure 3.

For the first-stage cooling radiation at 399 nm and for the lattice laser at 759 nm external-cavity-diode-lasers

(ECDL) based on narrow-band interference filters [Baillard 2006, Tackmann 2010] are being developed, which promise improved stability compared to the commonly used grating-stabilised ECDLs. A prototype interference-filter ECDL at 399 nm using standard laser diodes and delivering up to 40 mW has already been tested successfully as a master laser. It is used to inject another, free-running laser diode and provides light for initial atom slowing. The higher power of a few 100 mW that is required at the optical lattice wavelength of 759 nm will be achieved using a self-injected tapered amplifier.

A compact repumping laser at 1 389 nm, required to reduce fluctuations of the clock interrogation signal, has been developed. The unit is based on a DFB laser diode with fiber output,

and exhibits a low free-running frequency instability (about 15 MHz/day linear drift) that will allow using the laser without further frequency stabilisation.

The post-cooling laser at 556 nm is a laser system based on fiber laser technology. It is designed to have a total volume of 3 litre. The all-fiber optical setup consists of three stages. The seed signal at 1111.60 nm is generated by a NKT Photonics BASIK module. The infrared signal is amplified in an amplifier pumped by two pump laser diodes at 974/980 nm. Second harmonic generation (SHG) at 555.80 nm is performed by an all-fiber coupled waveguide periodically poled lithium niobate (PPLN) device. An output power of 20 mW has been achieved, exceeding the design goal by a factor of two.

The most sophisticated laser system is the clock laser system at 578 nm for which a stability and linewidth in the 1 Hz range are required. Our approach for providing the 578 nm clock radiation

is based on second harmonic generation of an external cavity quantum dot laser (QD-ECDL) at 1 156 nm, in a PPLN waveguide. The required laser stability has been achieved by stabilising the laser to a highly stable ULE reference cavity.

Atom preparation in the Strontium clock

The design of the first-generation compact vacuum apparatus, which is fully operational, is shown in Figure 4. Strontium atoms are first evaporated in a low-power-consumption oven working at 450–500 °C. The atomic beam is generated by a set of capillaries at the output of the oven and the atoms are then decelerated in a 30 cm long Zeeman slower and finally loaded into a 1st stage MOT, which uses the dipole-allowed 1S_0 - 1P_1 transition at 461 nm.

The typical number of loaded atoms is about 10^8 . By observing the expansion of the atoms from the MOT, an atomic temperature of about 2 mK was determined.



Figure 3. Overview of the laser system for the ytterbium lattice clock, comprising five lasers. Frequency stabilisation units for the first, second and fourth laser are not shown.

The second-stage MOT is applied on the $^1S_0 - ^3P_1$ transition at 689 nm. Pending availability of the newly developed 689 nm laser, a prototype master-slave laser delivering up to 50 mW has been employed. The slave laser is optically injected with a beam coming from the pre-stabilised master laser, with a frequency offset of 160 MHz from atomic resonance. In order to tune the laser frequency on resonance and to provide the necessary power level and frequency modulation for the 2nd stage MOT, a double-pass acousto-optical modulator (AOM) is used. Triggering of the associated synthesizer is performed by a computer-controlled FPGA. As shown in Figure 5, the 2nd stage MOT trapping and cooling consists of two main phases, A 120 ms long ‘broadband’ phase during which the frequency of the cooling laser is broadened to 5 MHz to cover the Doppler width of the atoms at the end of the 1st stage MOT, followed by 30 ms of ‘single-frequency’ phase. The broadband phase allowed cooling and trapping about 1×10^7 ^{88}Sr atoms at 22 mK, while the ‘single-frequency phase’ further cooled to the 2 mK level, with a final population of 1×10^6 atoms. The atoms are then loaded with about 50 % efficiency into a vertically oriented 1D lattice, realised by means of the new 813 nm laser source from this project.

Atom preparation in the Ytterbium clock

Within the first year of the project we have succeeded in preparing ultra-cold ensembles of the two isotopes ^{174}Yb and ^{171}Yb in a one-dimensional optical lattice which operates at 759 nm, the magic wavelength for Yb [Barber 2006]. Our approach for the realisation of such a magic-wavelength optical lattice includes enhancement resonators which are placed in the

vacuum chamber in which the cold Yb ensembles are prepared. Inside two perpendicular resonators a large-volume optical lattice (either one- or two-dimensional) can be formed with only a few 100 mW power from a diode laser (Figure 6 left). The resonator mirrors, two of which are mounted on ring piezo actuators, are glued to a monolithic structure, made out of the steel alloy invar, in order to increase the passive stability of the optical lattice. The end mirrors are transparent for the clock transition wavelength of 578 nm, which makes it simple to superimpose the radiation at the clock wavelength with the optical lattice.

Loading of a 1D optical lattice was so far achieved by using one of the two enhancement resonators with a beam waist of $\sim 150 \mu\text{m}$. We estimate that currently the maximum achievable trap depth is on the order of 50 μK . Yb atoms are loaded into the lattice by carefully aligning the position of the 2nd stage MOT to the lattice position and ramping down the 556 nm cooling light field (see Figure 6). Successful loading of the optical lattice is observed by turning the cooling light field back on after a variable hold time and detecting the fluorescence of the atom that remained trapped in the lattice in the meantime. Without the lattice light field, no atoms are recaptured after roughly 20 ms while with the light field recapturing is possible even after 300 ms. The longest lifetime in the optical lattice observed so far is 130 ms, sufficient for the operation of an optical lattice clock.

In the currently used prototype setup we can transfer more than 20 % of the atoms from the 2nd stage MOT into the optical lattice, amounting to roughly 10^5 atoms, as aimed for. Since the

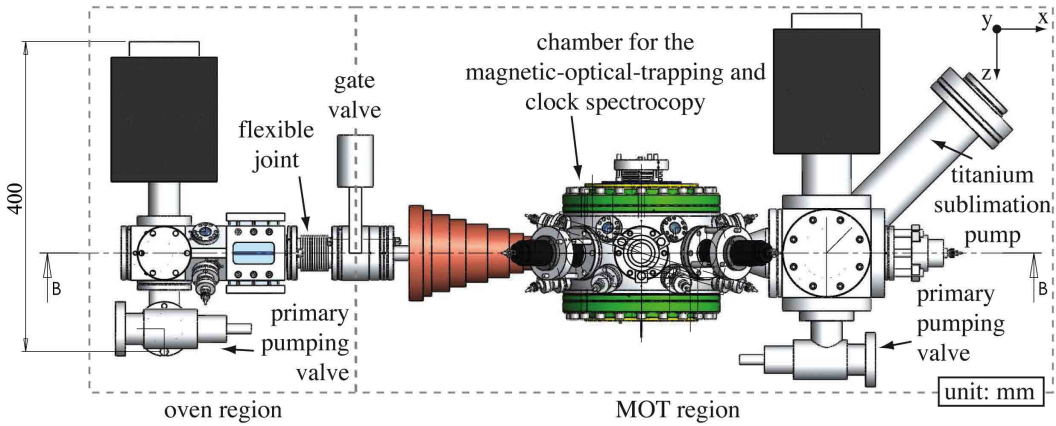


Figure 4. Section view of the 1st generation Strontium atoms package. Red, Zeeman slower. The extension of the vacuum system is about $110 \text{ cm} \times 35 \text{ cm} \times 40 \text{ cm}$, corresponding to a total volume of about 150 liters.

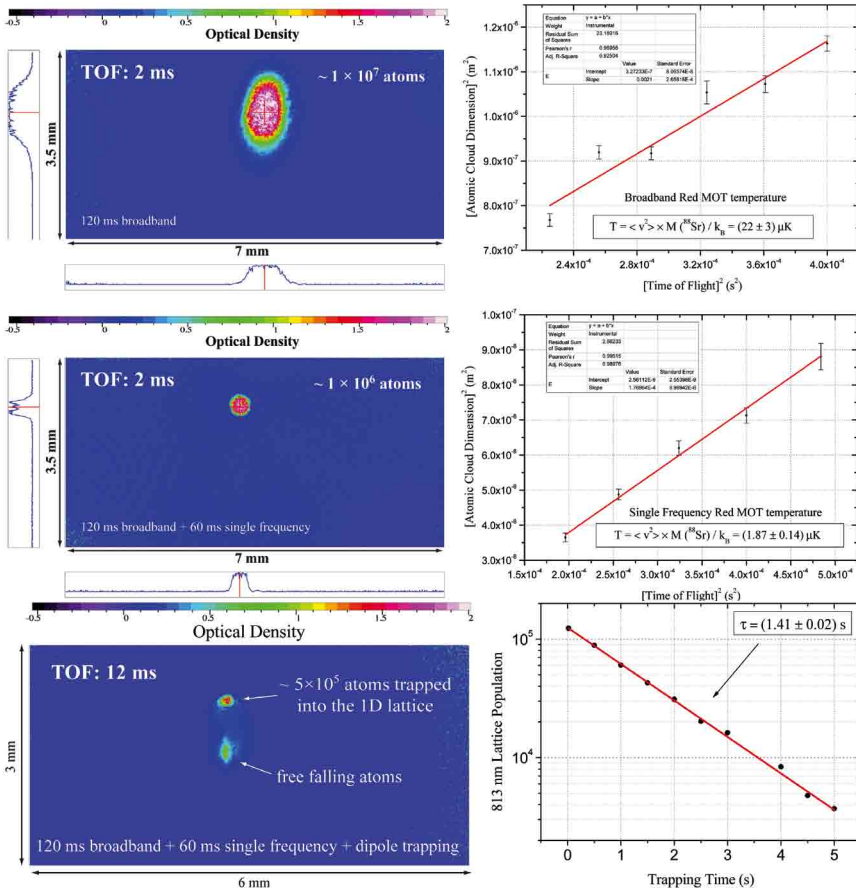


Figure 5. Top and centre: absorption images of the Sr atoms and time-of-flight (TOF) measurements of the temperature (graphs) at the end of the ‘broadband’ and ‘single-frequency phase’. Bottom: absorption image taken 12 ms after turning off the 689 nm beams. A significant fraction of the atoms remain trapped in the 1D lattice (813 nm), while the untrapped fraction falls in the gravitational field.

temperature of the atoms in the MOT is typically 30–50 μK we may infer that the transfer efficiency is limited by the depth of the optical lattice. This limit should be overcome in an advanced resonator setup, which is designed to allow for lattice depths of several 100 μK and higher transfer efficiency.

Next-generation subunits

The 461 nm cooling light for Sr is obtained by second-harmonic generation. As a potentially simpler and more robust alternative to the conventional generation in an external enhancement cavity (used in the laser developed for this project), we have tested the single-pass generation in periodically poled KTP waveguides (ADVR). We could couple fibres with waveguides such that the input coupling efficiency to the waveguide was up to 70 % (at 922 nm) and could obtain up to 40 mW of power at 461 nm. The output power could not be increased to more than 100 mW, as required. Therefore, an evaluation of different waveguide types is planned to follow.

For a transportable clock, robustness, compactness and moderate mass are desirable. In this respect, we have

compared two different techniques for realising the UHV environment in the atomic package: lead sealing and gluing. Although both techniques have yielded vacuum in the range of 10^{-11} – 10^{-12} mbar, the gluing technique has resulted in a more compact and lightweight vacuum chamber which can be baked well above 200 $^{\circ}\text{C}$. In the process, we have analysed different combinations of materials for the chamber, windows and glues. We have found that although several combinations are possible, MACOR/titanium for the chamber material together with BK7/YAG for windows is a good combination from the thermal expansion point of view. We have also found that the two adhesives H77 and 353ND work quite well.

Two novel approaches for loading atoms into a lattice optical clock are being investigated.

For the first approach, a two-dimensional (2D) MOT loaded from a dispenser is being tested. We have obtained some preliminary results where a 3D MOT is loaded from the 2D MOT system. We have observed clear enhancement in the atom number in the 3D MOT when loaded from the 2D MOT (Figure 7

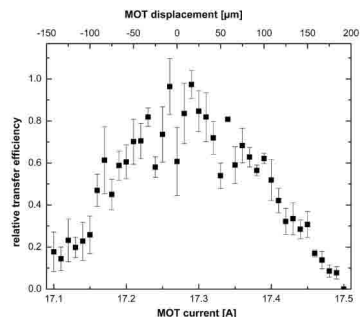
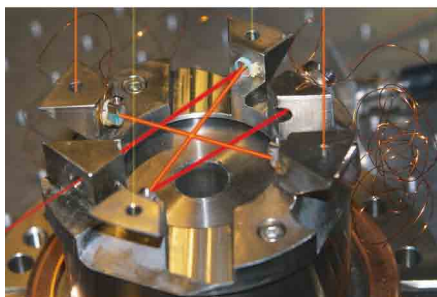


Figure 6. Left, photograph of the monolithic resonator setup for 1D and 2D optical lattices. Right, transfer efficiency into the optical lattice as a function of 2nd stage MOT position. The MOT position is controlled via the current through one of the MOT magnetic field coils.

inset). Having gained from the above experience, we have realised a preliminary design for a 2nd generation compact and lightweight vacuum chamber as required for the project (Figure 7 main).

The design is flexible in the sense that either a 2D MOT or a Zeeman slower can be used for slowing. The ultra-high vacuum will be maintained by

ion pumps. In addition to the optical access for lasers for 2nd stage cooling, detection, lattice trapping, etc, a thermal enclosure will be designed for the atomics package, which allows control of temperature to better than 0.1 K at the position of the atoms, necessary for controlling the blackbody systematic frequency shift. Closed-loop magnetic field control will also be installed.

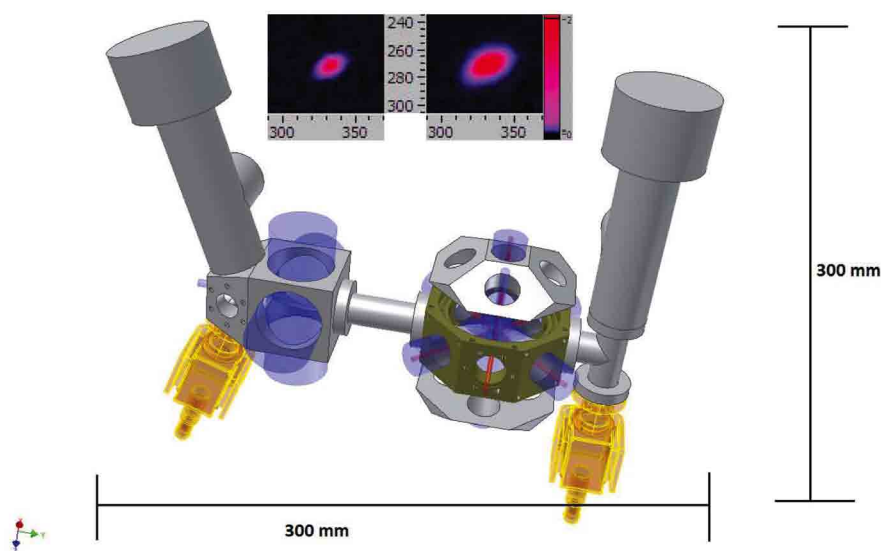


Figure 7. Main figure, preliminary design of the second-generation atomics package, where a 3D MOT (centre) will be loaded from a 2D MOT (left side). The design is also adaptable to a Zeeman slower replacing the 2D MOT. Blue: cooling and detection beams; red: 2nd stage cooling and lattice trapping beams; yellow: ion pumps. Inset, two images of a ^{88}Sr 3D MOT loaded without (left) and with (right) a 2D MOT on, in a separate setup. The enhancement of the atom number is clearly visible.

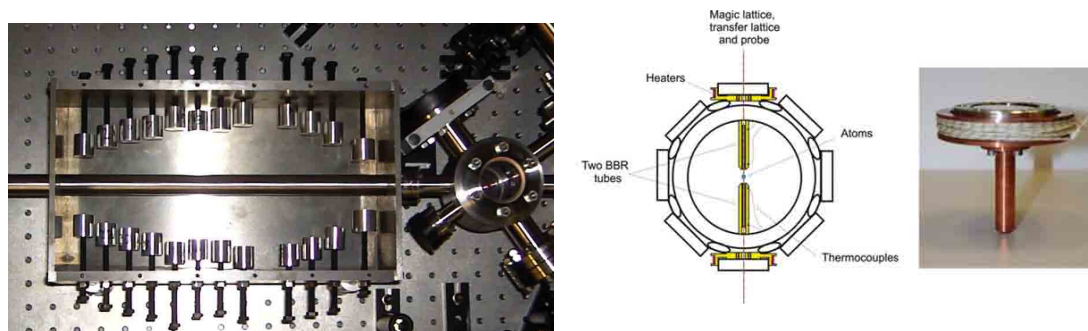


Figure 8. Left, top view of Zeeman slower using permanent magnets. Centre, schematic of MOT/lattice chamber with blackbody tubes. Right, photo of blackbody tube showing heater section external to UHV chamber.

The second, conventional, approach for capturing atoms and loading them into a lattice trap consists in slowing the hot atoms emitted from the oven using a Zeeman slower, as is done in the 1st generation breadboard (Figure 4). Typically, in a Zeeman slower a tapered solenoid is used. We have developed a novel transverse magnetic field Zeeman slower [Ovchinnikov 2008], which uses permanent magnets situated at adjustable distances from the beam axis (Figure 8 left), and which works equally well for both ^{87}Sr and ^{88}Sr isotopes. This has potential for achieving a clock apparatus with smaller footprint, reduced mass and no dissipation.

Finally, one of the major frequency shifts encountered in neutral atom lattice clocks is the black-body radiation shift due to the surrounding apparatus. Its value needs to be known in order to reach the goal accuracy of the space clock. We have developed a blackbody chamber to test calculations of the Sr black-body shift coefficient. The chamber includes two narrow copper tubes that approximate to well-defined black-body sources (Figure 8). Cold Sr atoms at micro-Kelvin temperatures will be transported into either tube by a moving-lattice beam, then transferred into the ‘magic-wavelength’ lattice for interrogation by the clock laser. By sequentially probing the lattice-trapped atoms in the two tubes at different temperatures, the differential blackbody shift is measured, allowing validation of the black-body coefficient.

CONCLUSIONS

The new Sr laser subsystems have in part been integrated with the Sr

atomics subsystem and have already allowed trapping Sr atoms in the optical lattice. Once fully integrated, we expect to be able to provide and to interrogate cold atomic samples with desired features. The subunits of the Yb clock are also working well individually, with the atoms routinely trappable in the optical lattice. The upcoming work for the 2nd year of the project will include (i) completion of the integration, spectroscopy of the clock transition, initial characterisations of the clocks’ performances, and optimisation; and (ii) progress on the development of the second-generation subunits (lasers, atomics package components), so that they can be integrated into the clocks in year 3.

Preparatory activities are also in progress for the later robustness testing of lasers and for the full characterisation of the transportable optical clocks after moving them from the integration labs to national metrology labs, and for next-generation compact optical frequency combs.

At the end of the project we expect to have an operational lattice clock that will represent the baseline design for the production of the flight model for the ISS space clock.

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