PROJECT FINAL REPORT

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Project acronym: SOC2
Project title: SOC2—Towards Neutral-atom Space Optical Clocks: Development of high-performance transportable and breadboard optical clocks and advanced subsystems
Funding Scheme: Collaborative project
Period covered: from 3/2011 to 11/2015
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4.1 Final publishable summary report

Executive summary

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 program of ESA, the “Space Optical Clocks” (SOC) project aims to install and to operate an optical lattice clock on the ISS towards the end of this decade, as a natural follow-on to the 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) (2011-2015) had the goal to develop two “engineering confidence“, accurate transportable lattice optical clock demonstrators having relative frequency instability below 1E-15 at 1s integration time and relative inaccuracy below 5E-17. This goal performance is about 2 and 1 orders better in instability and inaccuracy, respectively, than today’s best transportable clocks. The devices are based on trapped neutral ytterbium and strontium atoms. One device would be a breadboard. The two systems would 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 developed a large number of laser systems - adapted in terms of power, linewidth, frequency stability, long-term reliability, and accuracy. Novel solutions with reduced space, power and mass requirements were implemented.

A completely new, compact strontium lattice clock was built, occupying approximately two racks (2 cubic meter) and having 1.1 kW power consumption. This apparatus was transported from Birmingham to Braunschweig, for optimization and characterization. It is fully functional (http://arxiv.org/abs/1603.06062). The clock transition of bosonic strontium was observed with < 4 Hz linewidth and preliminary measurements showed a frequency instability of approximately 1E-16 for integration times up to 2 000 s.

A transportable fermionic Yb clock apparatus was completed and underwent preliminary characterization (12 Hz clock transition linewidth). It was transported from Düsseldorf to Torino, where characterization is continuing.

Summary description of project context and objectives

Atomic clocks are essential tools in modern society. Clocks operate in computers, data networks, are ubiquitous in scientific applications and are even operated in satellites, especially in navigation systems such as GPS, GLONASS and the currently developed European Galileo system. Time, or more precisely, time interval, is the most precisely measurable quantity. Since the speed of electromagnetic waves in vacuum is invariable, distance measurements can be performed by propagation time measurements. Thus, ultimately the precision of distance measurements is limited by the available precision in time measurements.

In the International System of Units, the unit of time, the second, is based on an atomic hyperfine transition in neutral cesium (Cs) atoms. Laboratory clocks using cold Cs atoms have an inaccuracy of several parts in 10^{16} today. Although this is already by far the lowest inaccuracy of any physical unit, a major scientific development over the last decade, namely clocks based on optical rather than microwave transitions, has opened a new era in time/frequency metrology. In optical clocks the (laser) electromagnetic wave beats 10^{15} times per second instead of 10^{10} as in microwave clocks. Therefore, one can detect (and also correct) a minute change of the period much faster, allowing an enhanced stability. In addition, several perturbing effects on the energy levels of the employed atoms are smaller in relative terms for optical transitions compared to microwave transitions, and a large gain is therefore also possible in the accuracy. Optical clocks have now achieved a performance significantly beyond that of the best microwave clocks, at levels now below 1×10^{-17} relative inaccuracy. It is therefore expected that in the mid-future the unit of time will be redefined via an optical transition.

The essential techniques used in optical clocks are the confinement of the atoms to regions significantly smaller than the wavelength of light, provision of an environment as free of disturbing influences (magnetic and electric fields, residual gas, black-body fields) as possible, choice of adequate atomic species, and the narrowing of the spectral width of the clock laser to relative levels of 10^{-15} and less. Accurate comparisons of optical frequencies of these clocks or relative to the Cs atomic time unit are performed using femtosecond laser frequency combs. Several Physics Nobel prizes were awarded for methods that have enabled optical clocks.

With the rapidly improving performance of optical clocks, it will only be possible to take full advantage of it by operating them in space, since on Earth the clock frequency is influenced by the Earth's gravitational potential at the location of the clock, contributing with an uncertainty on the order of one part in 10^{17}, which may drift in time e.g. from tidal effects. Therefore, in the future, most applications requiring the highest accuracy will require operating optical clocks sufficiently far away from Earth, e.g. in a geostationary orbits. Such clocks will then become “master clocks in space”. A range of new applications will be enabled by ultra-precise optical clocks in near or deep Space, in part in conjunction with terrestrial clocks. These applications have been widely discussed, proposed and evaluated by review panels of ESA. They cover the fields of fundamental physics (tests of General Relativity and its foundations), time and frequency metrology (comparison of distant terrestrial clocks, operation of a master clock in space), geophysics (mapping of the gravitational potential of the Earth), and potential applications in astronomy (local oscillators for radio ranging and interferometry in space). In particular, one project in the ELIPS program of ESA targets operation of a high-performance lattice optical clock on the ISS for fundamental physics and Earth science in approx. 2024. Thus, the development of a space optical clock of performance significantly higher than the current state-of-the-art (microwave) space clock PHARAO is an important as well as challenging task for this decade.

Topic addressed in the call

Our proposal responded to “Activity: 9.2. Strengthening the foundations of Space science and technology”, sub-activity “SPA.2010.2.2-01 Space technologies”, and herein to the item “Optical Clock Time Referencing System” (Technology Domain: Opto-Electronics) as described in the EC-ESA-EDA LIST OF URGENT ACTIONS FOR 2009 [ESA09]. **It calls for the “Development of an Optical Clock demonstrator for ultra-high precision timing referencing applications”**.

Objectives

For the ultra-high precision required in the call we target a level beyond that of the best space clock, PHARAO, the compact microwave clock based on cold Cs atoms that has recently been developed as an engineering model for the ESA ACES mission (planned for 2017).

Thus, the goal specifications for the demonstrator were set to be an instability below $1\times10^{-15}/\square^{1/2}$, and an inaccuracy below 5×10^{-17}, in a package of less than 1000 liter, excluding electronics. With this enhanced performance, fundamentally new applications will become possible, as mentioned above. In addition it will allow the comparison of the best ground clocks, within much shorter averaging time even compared to ACES with higher accuracy.

The proposers are convinced that optical clocks based on neutral atoms trapped in a laser light lattice offer a good balance between the performance potential (instability and inaccuracy) and moderate complexity. Thanks to the developments already performed in the laboratories of the proposers, this project will permit to develop high-precision demonstrators that represent a first step towards a space lattice clock of significantly improved performance compared to the best current space clock.

Thus, the main objective of this work was the development and characterization of two high-performance optical clock demonstrators with the above target performance and with dimensions and design that qualify them as breadboard and transportable, respectively.

The secondary objective was to develop and test components and sub-systems that will lead to enhanced compactness, robustness and longevity of the optical clocks.

Both objectives have a direct relevance to later implementation as a space instrument.

Objectives of this project

1.) Develop two transportable engineering confidence optical clock demonstrators with performance

Instability $< 1\times10^{-15}/\square^{1/2}$

Inaccuracy $< 5\times10^{-17}$

This goal performance is about 2 – 3 orders better than today’s best transportable optical clock based on room-temperature Doppler-free molecular spectroscopy, and better than the best microwave cold atom clock by a factor 100 and approx. 10, in instability and inaccuracy, respectively.

Compared with the stationary laboratory clocks at the time of submission of the proposal (2009), the inaccuracy goal is about a factor 2 better than the level of today’s best neutral atom laboratory clocks and the stability goal is equal.

The two systems are to be brought to TRL4 (validation in a laboratory environment).

2.) Develop the corresponding laser systems (adapted in terms of power, linewidth, frequency stability, long-term reliability), atomic package systems with control of systematic (magnetic fields, black-body radiation, atom number), and an electronic and computer control system, where novel solutions with reduced space, power and mass requirements will be implemented. Some of the laser systems will be developed to 2nd generation level with emphasis on even higher compactness and robustness. Also, some laser components will be tested at TRL 5 level (validation in relevant environment).

List of participants

Participant	Participant organisation name	Acronym	**Country**
1 coordinator	Heinrich-Heine-Universität Düsseldorf	HHUD	**DE**
2	Physikalisch-Technische Bundesanstalt	PTB	**DE**
3	Leibniz Universität Hannover	LUH	**DE**
4	Observatoire de Paris	OP	**FR**
5	Università degli Studi di Firenze	UNIFI	**IT**
6	Istituto Nazionale di Ricerca Metrologica	INRIM	**IT**
7	University of Birmingham	UOB	**UK**
8	National Physical Laboratory Teddington	NPL	**UK**
9	TOPTICA Photonics AG	TOPTICA	**DE**
10	Kayser-Threde GmbH (now OHB)	KT	**DE**
11	EADS Astrium Friedrichshafen	ASD	**DE**
12	Menlo Systems GmbH	MENLO	**DE**
13	Kayser Italia Srl	KI	**IT**
14	Université de Neuchâtel	UNEU	**CH**
15	Centre Suisse d’ Electronique et de Microtechnique SA	CSEM	**CH**
16	Ecoles Polytechniques Fédérales Lausanne	EPFL	**CH**

Main S&T results/foregrounds

Work package: WP1: Baseline laser systems

The complete laser system for strontium (Figure 1.1) has been realized and the individual modules tested at each respective institute.

In a first test at UNIFI the relevant laser sources (813 nm, 689 nm, 461 nm) were integrated with the frequency stabilization system unit (FSS), to which the basic cooling and trapping lasers have been frequency-referenced. The basic laser system was fully operational and was been used to perform high resolution spectroscopy on the clock $^1S_0$-$^3P_0$ transition for the ^{88}Sr isotope. For experimental test of the clock performances, a stationary clock laser and stationary RF reference were employed.

Later, the complete laser set was been shipped to University of Birmingham (UBHAM) for the integration in the 2nd generation Sr breadboard (deliverable 4.5). Now, the laser set is still integrated and routinely in operation at PTB.

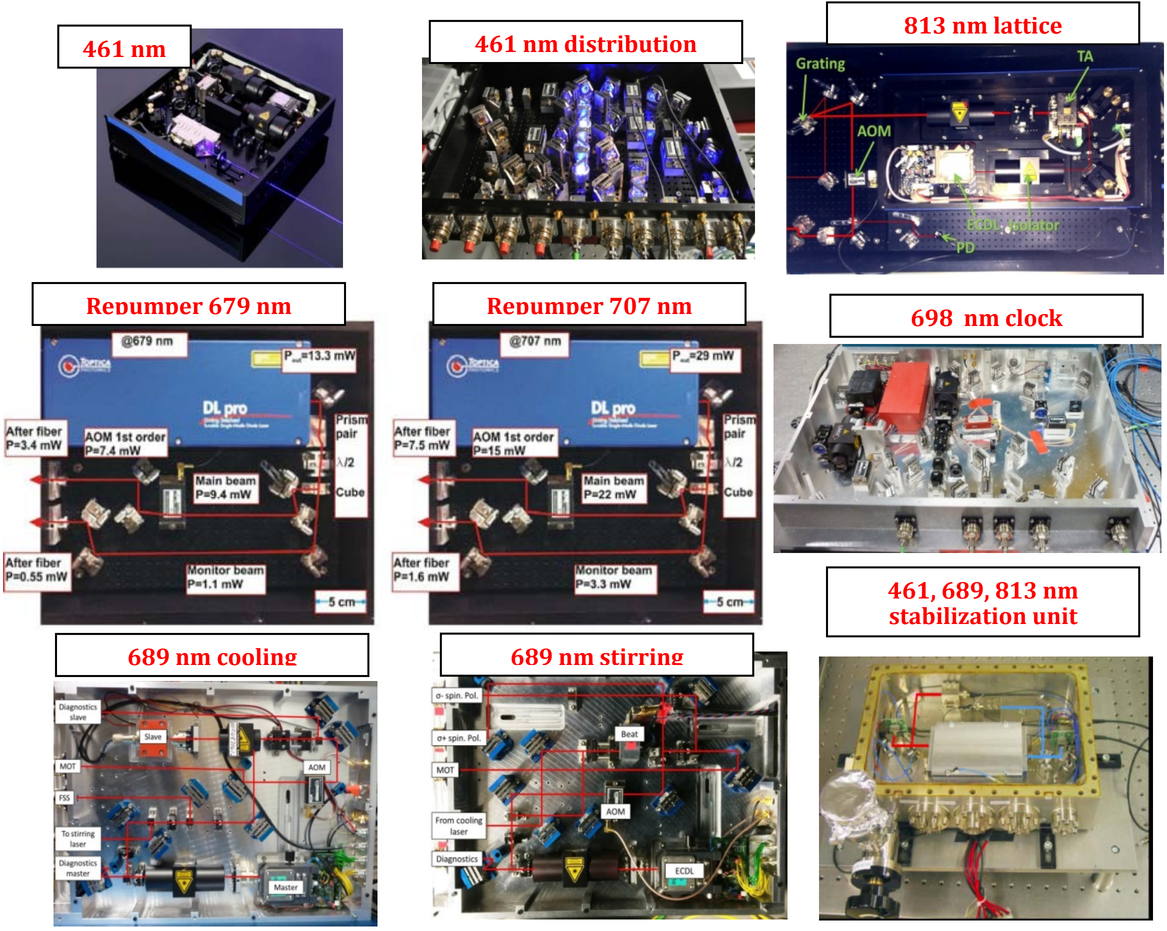


Figure 1.1 The laser subsystems for the 2nd generation Sr clock apparatus.

Below is reported a detailed description of the status for each subsystem (Internal deliverables D1.1 - D1.5 and deliverable D4.5).

D1.1 - 813 nm MOPA laser with breadboard *(Development of breadboard for generation and distribution of 813 nm light for operation of the optical lattice with output power after fiber of approx. 300 mW.-UNIFI-)*

The 813 nm source has been integrated on the 1st generation cold strontium apparatus. First experimental tests showed high transfer efficiency (up to 50 %) from pre-cooled ^{88}Sr atoms in red MOT and a lifetime of 1.4 s (without frequency or amplitude stabilization of the lattice light).

The laser has been stabilized to the FSS and we observed no spurious effect (broadening or shift) on the clock transition frequency (see report 4.1 for more details).

The 813 nm has eventually been upgraded with a 1W tapered amplifier by TOPTICA. The distribution breadboard has been finalized and shipped to UBHAM and later came back together with the atomic package to PTB.

D1.2a - Tested cooling laser system (689 nm) for Sr *(Development of one breadboard for the 689 nm cooling laser and one for the 689 nm stirring and spin-polarization laser -PTB-).*

The breadboards have been finalized. The cooling laser has been fully assembled, stabilized to the FSS and integrated at UNIFI with the Sr cold atoms apparatus. This breadboard was been shipped to UBHAM and later came back together with the atomic package to PTB.

D1.2b Tested repumper laser system for Sr distribution breadboard *(Development of compact laser breadboards for atom cooling and manipulation in a Sr lattice clock: one breadboard for 707 nm and 679 nm repumpers - UNIFI-)*

The two Toptica repumper lasers have been integrated on the 1st generation Sr breadboard for normal operation of the Sr MOT.
Thanks to their passive frequency stability, no need of frequency stabilization seemed to be required (in standard temperature condition of laboratories at UNIFI). The compact breadboards have been finalized and shipped to UBHAM and later came back together with the atomic package to PTB.

D1.3 Tested clock laser system for Sr *(Development of a clock laser at 698 nm and compact clock laser control and distribution breadboard with fiber coupling to reference resonator. Optimize existing reference cavity from SOC-I -PTB-. Build generic fiber coupled filter stabilized extended-cavity diode lasers for breadboard and additional cavity tests.-LUH-)*

The Sr clock laser system has been completed and transported at UNIFI where it has been integrated with the Sr cold apparatus. First tests with a stationary clock laser showed beat notes with linewidth of about 1Hz, consistent with laser specification. The best resolution obtained on atomic spectroscopy signals was around 8 Hz.

D1.4 Frequency-stabilized DFB laser (1389 nm) with > 5 mW *(Development of a very compact repumper 1389 nm laser for Yb based on commercial fiber-pigtailed DFB laser. Build compact clock laser control and distribution breadboard with fibre coupling to reference resonator -UDUS-)*

The 1389 nm laser (Figure 1.2) has been successfully developed. It is a unit with a fiber output, and good free-running frequency stability (about 15 MHz/day linear drift). The system is currently in use on the Yb atomics package.

Figure 1.2 The 1389 nm repumper laser for the Yb clock

***D1.5 461 nm laser and frequency distribution system** (Development of an optimized fiber distribution system for 1st and 2nd stage cooling light and a frequency distribution system for 461 nm light)*

A new optimized fiber distribution system (based on dichroic fiber launcher and achromatic optics) has been developed and assembled. It has been integrated with the 1st generation Sr breadboard. The system is highly reliable. During 20 months of experimental tests no re-alignment of the MOT beams has been necessary.

A new frequency distribution module, to be used with the second-generation Sr breadboard, was built at UBHAM according to UNIFI specifications during year 1. It is seen in Figure 1.1, and is currently in use with the apparatus at PTB.

Internal deliverable D4.5: “Transfer of Sr laser breadboards, fiber cluster and frequency stabilization system”

After extensive tests on the first generation clock all the laser sources integrated at UNIFI have been removed and shipped to UBHAM for integration with the 2nd generation apparatus in October 2013. The laser system includes:

- 689 nm cooling and stirring lasers,
- Frequency stabilization system (FSS),
- 461 nm blue laser source,
- 679 nm and 707 nm repumpers
- 813 nm laser (upgraded with 1W tapered amplifier from TOPTICA)
- All the TOPTICA and custom made electronics for frequency stabilization have also been shipped.

The 698 nm laser was shipped to PTB and was integrated with the 2nd generation cavity from SYRTE.

In the internal planning, it had been decided that the deliverable includes 3 x 3 fiber cluster for interfacing between the laser breadboard and the atomics chamber, purchased from funds allocated to UNIFI in this WP. The originally intended commercial device was, however, not purchased, since in a similar unit, too low efficiency was achieved. Therefore a higher efficiency, home-made unit was designed and built. After a successful experimental test at UNIFI, the design has been provided to UBHAM, where the system has been eventually assembled and implemented on the 2nd generation strontium clock.

Milestones 1, 2, 3, 4 were fully achieved.

Work package: WP2: Advanced laser systems

Work package 2 contains the assembly of light sources for cooling and trapping Strontium and Ytterbium atoms, respectively, the realization of ultra-stable laser systems for clock operation and the development of optical cavities for frequency stabilization, as well as advanced frequency combs.

A. Deliverable 2.1 “Advanced Lasers for Sr clock”

D2.1 (internal deliverable number) “Compact Sr lasers frequency stabilization module (FSS) with fibre incoupling and computer control” (by NPL, UDUS, UNIFI)

The FSS was shipped to UNIFI in early January 2013. The stabilizations of the 689, 922, and 813 nm lasers to the cavity were implemented. Sr atoms were loaded successfully into the lattice and the clock transition was detected.

The system was subsequently shipped from UNIFI to UBHAM in October 2013 and integrated successfully in the 2nd generation atomics system, where it is still operational.

A publication on the FSS has been written and published in Optics Letters.

Milestone 5 “Compact multi-wavelength stabilization unit for frequency stabilization of the Sr lasers” has been reached.

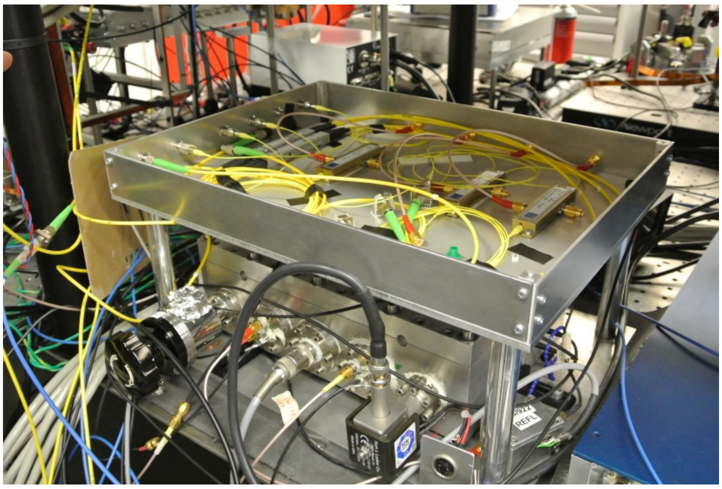


Figure 2.1: The frequency stabilization system (FSS). On the bottom is the vacuum chamber with the reference cavity. On the top is a box with the waveguide electrooptic modulators for side-band locking, and the waveguide splitters. Center front is the small ion pump for evacuating the chamber.

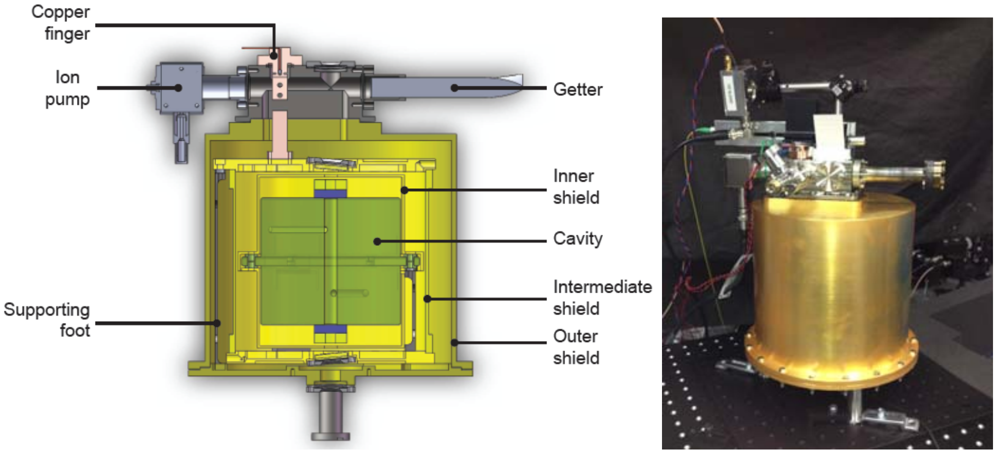


Figure 2.2: Left: design of the robust reference cavity. It is characterized by a robust mounting, a 10 cm long vertical (in the case of ground use) ULE cavity, and 2 thermal shielding layers. Right: Titanium vacuum system.

D2.3 (internal deliverable number): "Prototype of the cavity, integrated in its vacuum and thermal environment" (by OP)

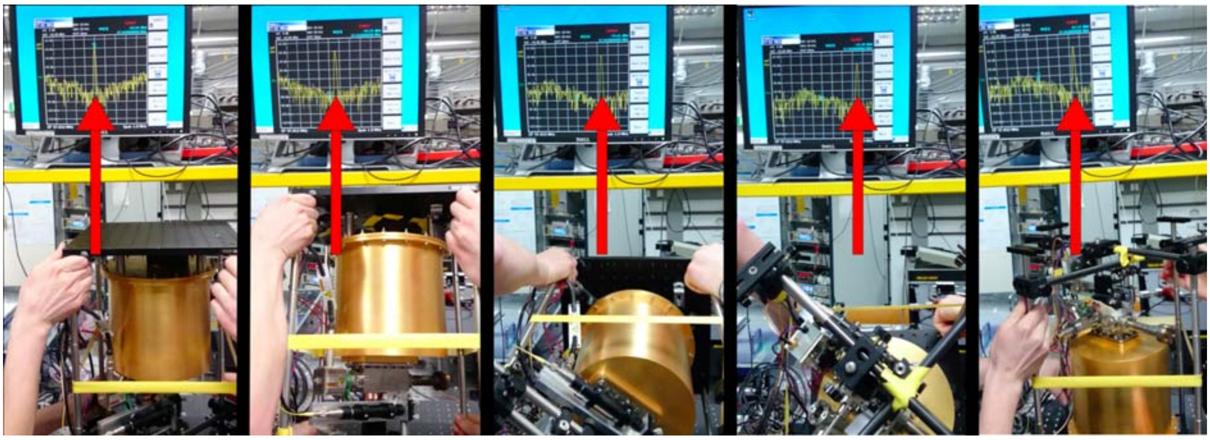
As the purchase of a modified cavity failed, a commercially available cavity assembly, which became recently available, has been purchased. This system (Figure 2.2) is based on a 10 cm long cavity, with fused silica mirrors and with compensation rings. The design is transportable, with low acceleration and temperature sensitivity. This system is interesting to test because it provides a cost-effective way to realise a high-performance ultra-stable laser that can be useful to many laboratories and many applications.

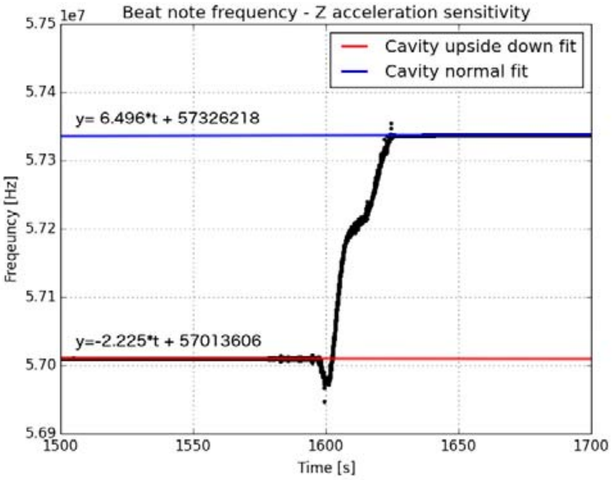
The necessary vacuum parts, temperature stabilisation parts and a few mechanical and optical parts (fibre coupled input into the cavity) were designed and manufactured, aiming at a total weight of 8 kg.

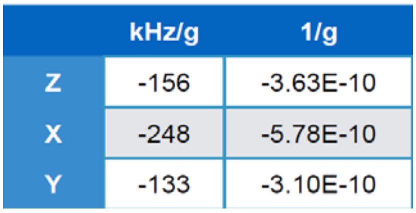
D2.12 (internal deliverable number): "Complete, cavity-stabilized clock laser systems and test in clock environment."

The cavity was brought from Paris to PTB by car in November 2014, where it was installed on an active vibration-isolation table and integrated with the 698 nm laser breadboard. The necessary modulation for the Pound-Drever-Hall (PDH) lock was performed by a fibre-coupled low voltage waveguide EOM. As the output power of the filter-stabilized laser from LUH was sufficiently large to drive all optical output signals, the original master-slave setup on the breadboard was modified to only use a single laser, which considerably simplifies the setup and improves reliability.

The cavity-stabilized laser system was characterized in comparison to PTB's stationary clock laser. First, the vibration sensitivity was determined by rotating the whole cavity in different directions, while observing the corresponding beat frequency (Figure). The resulting sensitivities are reasonably small, so under the residual vibration levels of 1 µg expected on the ISS with the addition of an active vibration isolation system, instabilities in the 10^{-15} range are reachable.







	kHz/g	1/g
Z	-156	-3.63E-10
X	-248	-5.78E-10
Y	-133	-3.10E-10

Figure 2.3: Top: snapshots of the reference cavity being rotated by hand. The clock laser remains locked to the cavity. Its beat with a stationary laser is displayed in the background on the spectrum analyzer. Bottom left**:** Frequency change in time, when the cavity is flipped upside down (z-direction), amounting to 0.3 MHz. Bottom right: measured vibration sensitivities of the clock laser setup (x,y: horizontal directions).

Second, the sensitivity to fluctuations of the laser power that is coupled in the cavity and that is partially absorbed by the mirrors was investigated. This power leads to heating of the mirror coatings and mirror substrates, and thus to a corresponding length change. A rather large value of 163 Hz/µW was observed, therefore a power stabilization circuit was implemented, which takes the transmitted power as input and uses AOM1 on the breadboard that introduces the frequency offset between laser and cavity as a servo element.

A severe problem concerning frequency stability was due to pressure fluctuations in the vacuum chamber. This could be traced back to leaks in the bottom indium seal of the chamber, which could not be fastened more tightly because of insufficiently strong screws. Nevertheless, during times with stable pressure, an Allan deviation below 2×10^{-15} could be observed (Figure) close to the required 5×10^{-16} for $0.1\ \text{s} < \tau < 10\ \text{s}$.

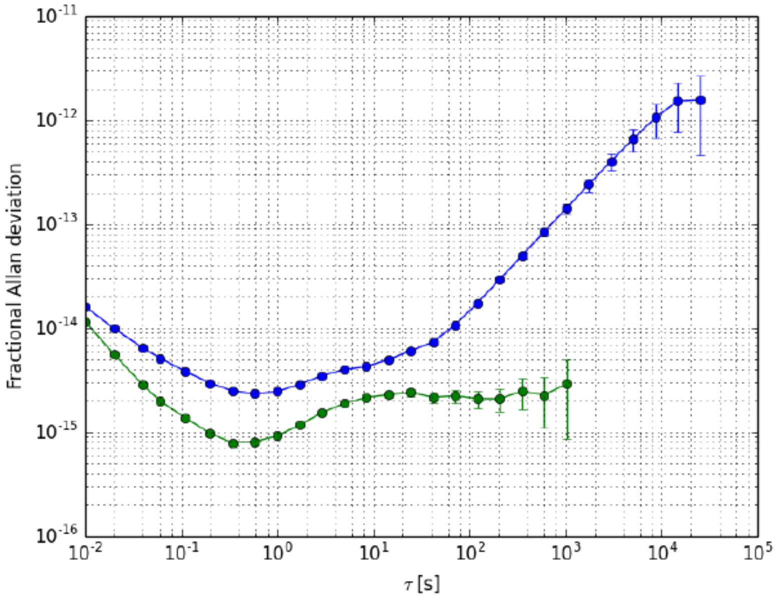


Figure 2.4: Fractional Allan deviation (linear drift removed) of a beat note against stationary system. Blue points present all-day (24h) measurement. The best 1-hour slot within all-day measurement was found by a script and is plotted with green points.

Later, the leak was reduced by applying additional clamps to the bottom of the vacuum system to increase the force on the seal. This lowered the ion pump current from 60 µA to 5 µA, however, there are still current excursions up to 15 µA (approximately 10^{-6} mbar). Maybe the pump was already degraded from extended operation at high pressure.

The spectroscopy of ^{88}Sr could be done with a smallest linewidth of approximately 40 Hz, with the clock laser in its present conditions. Improvements to the reference cavity will be attempted in the near future.

Milestone 12 “Demonstrate the performance of the second generation Sr cavity” was partially achieved.

D2.7 (internal deliverable number): “Technical Note on Risk analysis for the development of a space version of the cavity” (by OP and PTB)

The analysis of the initial prototype was published previously: B. Argence, E. Prevost, T. Lévèque, R. L. Goff, S. Bize, P. Lemonde, and G. Santarelli, *Prototype of an ultra-stable optical cavity for space applications,* Opt. Express **20**, 25409-25420 (2012).

The analysis was extended, taking the current SOC2 ultrastable cavity as a prototype for a future space mission. Based on the SOC2 results, the main risks for future development of a transportable ultrastable laser at 698 nm were worked out. Details are found in Deliverable 2.1.

D2.9 (internal deliverable number): “Comparative performance data for frequency doubling concepts using fibre coupled waveguides. Integration results of best system in the breadboard prototype.” (By UOB)

UOB tested a ppKTP waveguide from NTT, provided by Menlo Systems, which arrived in Birmingham during month 27.

The 461 nm light coming out of the waveguide was split into two paths: 5 mW going to the spectroscopy for locking the master laser to the Sr transition and the remaining output was transported to the 3D MOT chamber via fibre. As experimental result, UOB trapped Sr atoms in a 3D blue MOT.

The total output power achievable was not sufficient for reliable use in the Sr breadboard. Therefore we used as “best system” the system from partner TOPTICA (resonantly doubled high-power 922 nm laser).

In this sense more tests are needed before the technology could be fit for space missions: at the moment, the technology still appears to be fragile.

Milestone 11 “Demonstration of laser cooling of Sr with a waveguide doubled laser” has been reached.

B. Deliverable D2.2 “Advanced Lasers for Yb clock”

D2.2 (internal deliverable number): “556 nm Fibre Laser design“ (MENLO)

The all-fibre coupled 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 2 pump laser diodes at 974/980 nm. The second harmonic generation (SHG) at 555.80 nm is performed by an all fibre coupled waveguide PPLN device. Required power level after the SHG stage is more than 10 mW. See below at D2.6 for continuation.

Milestone 6 “New 556 nm laser design” has been reached

D2.4 (internal deliverable number): “Complete high-performance compact 578 nm Yb clock laser system” (by UDUS, INRIM)

As reported in the second project period, UDUS set up a home-built ECDL at 1156 nm with intra-cavity electro-optic modulator which could be locked to the first generation ULE reference cavity obtaining a laser linewidth of 1 Hz. However, the relatively narrow regulation bandwidth of the laser stabilization (approx. 100 kHz, limited by a mechanical resonance in the EOM crystal) did not allow a robust long-term operation of the stabilized laser, which was very sensitive to acoustic perturbations.

Recently, laser diodes at 1156 nm with an improved technology became commercially available, allowing an extended modulation bandwidth of 250 kHz. The new laser diode was implemented in a modified ECDL laser setup designed at UDUS and successfully locked to a high-finesse cavity using a direct current modulation.

The 2nd generation ULE reference cavity of octagonal shape was obtained in working condition only after a long and difficult process. In the end, the company ATFilms performed a cleaning and provided the cavity in working conditions.
The complete setup of the 2nd generation Yb clock laser system is shown in Fig. 2.5.

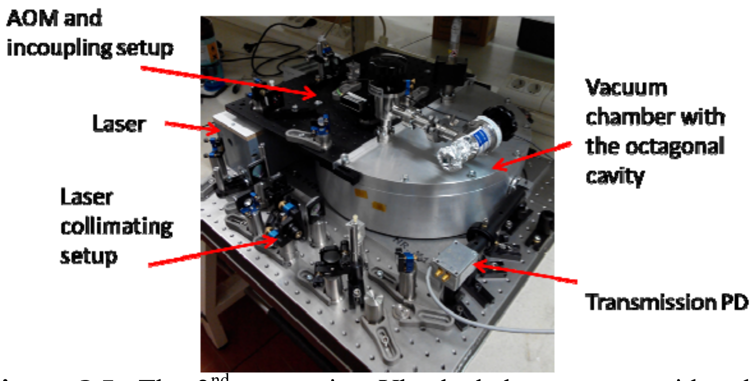


Figure 2.5: The 2nd generation Yb clock laser setup, with a home-built laser and an octagonal reference cavity.

The complete system was assembled on a compact 60 cm x 60 cm breadboard (itself supported by an AVI table). It demonstrated a high level of robustness – no misalignment occurred after the transportation of the system from Düsseldorf to INRIM, Turin. The home-made diode laser at 1156 nm could be stably locked to the high-finesse cavity using only the modulation current. The high output power of the laser together with the fiber coupled doubling waveguide allowed obtaining > 2 mW of radiation at 578 nm, even without an additional semiconductor optical amplifier. The laser and the waveguide were in operation for several months; no degradation in the performance has been observed.

The chosen construction of the octagonal cavity allowed developing a transportable system which does not require realignment of the laser beams.

So far, the performance of the system is not yet at a level to be useful for a high-performance optical clock. Further investigations and improvements of the cavity are required to reduce the vibration sensitivity by optimizing the supports. Another improvement should be done on the temperature isolation of the cavity, by adding an additional shielding inside the vacuum chamber.

Milestone 7 "Complete second generation Yb clock system with 5 mW" has been partially reached.

D2.6 (internal deliverable number): "Fibre laser with 10mW @ 556nm, fibre coupled" (by MENLO)

Deliverable D2.2 has been successfully integrated into the experiment at UDUS giving 15 mW of optical output power at the required wavelength. All required specifications have been reached. The laser is routinely in use on the Yb clock apparatus and the clock transition has been observed with 12 Hz linewidth (see WP4).

Milestone 8 "New Fibre laser system with 10mW @ 556nm fibre-coupled " has been reached

D2.8 (internal deliverable number): "High power filter stabilized laser module (2 units)" (by LUH)

Within the third project period, the second laser module has been finished at LUH. The delivery of the second laser was delayed due to a malfunction in the TA chips reported in the project report of Year 2. The laser was handed out to UDUS in Month 32. The additional delay was caused by temperature control malfunction of the laser modules.

The inherent (Lorentzian) linewidth of the lasers as well as the broadened (Gaussian) linewidth have been measured in a beat note measurement of the two laser modules that have been built. A Lorentzian curve fit allows us to deduce a beat note width of 197 kHz. Presuming the two lasers feature the same linewidth, we can infer the linewidth of a single laser to be 140 kHz which is significantly smaller than the specified linewidth of 300 kHz. The broadened linewidth of the unstabilized lasers is inferred using a Gaussian fit. From this, the beat note FWHM is found to be 745 kHz, which results in a single laser stability of 530 kHz. This linewidth could in principle be strongly reduced using a Pound-Drever-Hall type stabilisation.
During the current reporting period, the first laser showed a reduced output power and increased flashpoint current of approximately 1040 mA. It was possible to reduce the laser threshold current again by optimizing the cavity lens position.

One of the laser modules was tested at UDUS for its usability for the transportable optical clock apparatus. The tests were performed by coupling the laser output into the new enhancement resonator before it was integrated into the Yb optical clock apparatus in spring 2014. The results showed that the resonator as well as the laser were operating as expected. From the reflection spectrum, an efficiency for coupling of the laser into the resonator of higher than 60% could be inferred. In view of the delays that had already occurred the new laser module was not integrated into the Yb atomic source before the system was moved to Torino as this might have cost additional time. Nevertheless, our results indicate that the laser module is well suited for operation as a lattice laser in the Yb optical clock apparatus.

Milestone 9 "Demonstrate usability of compact filter stabilized high power laser in clock operation" has been partially achieved. Coupling of the radiation of the laser system into the enhancement has been demonstrated. Thus the milestone is partially achieved. For full completion of the milestone, stabilization of the laser to an enhancement resonator has to be demonstrated.

D2.10 (internal deliverable number): "Interference-filter based ECDL at a wavelength of 399 nm for laser cooling of ytterbium and test results" (by UDUS and LUH)

As described in the project reports of Year 1 and Year 2, UDUS and LUH successfully demonstrated a prototype ECDL at 399 nm with interference filter as frequency-selective element, both fulfilling the specified power requirements of 30 mW. Unfortunately, the UDUS laser showed a degradation of output power and frequency stability after several months of successful operation in the clock apparatus, which is mostly due to degradation of the laser diode and coating damages of the optical components.

After the shipment of Laser 1 from LUH to UDUS in month 23 of the SOC2 project, a shift of the emission wavelength of the laser diode to longer wavelength was observed which finally made it impossible to tune the diode to the Yb transition wavelength.

Therefore another ECDL (Laser 3) was set up at UDUS based on a test sample NDUA116T anti-reflection coated diode (also from Nichia Corp.) with a shorter specified emission wavelength (390 nm – 400 nm) but a lower specified output power (25 mW). In a configuration with a 30% reflector, UDUS achieved a useable output power of 12.7 mW at 47.4 mA with a diode temperature of 27.5 °C and a base temperature of 23 °C. The ECDL can be tuned reliably to the Yb transition wavelength with an overall tuning range of ~ 2 GHz. Laser 3 has successfully been integrated into the laser cooling breadboard.

Milestone 10 "Fully characterized laser system at 399 nm with a linewidth below 1 MHz and power > 30 mW " has therefore been achieved, albeit with slightly reduced specifications. The new version of the UDUS interference-filter ECDL (Laser 3) is integrated into the Yb clock apparatus (P = 12.5 mW). The characterization of the laser system is achieved through successful and stable operation of the Yb MOT.
The setup of a second 399 nm ECDL prototype, which had been postponed in the last reporting period due to a delivery delay of the diode, has been continued in the present reporting period. The new diode was a RLT400-50CMG from Roithner Lasertechnik, specified with 50 mW at 400 nm. For some reasons, this diode showed the same malfunction. as the second NDV4411T diode (see previous report). The reason for the failing lasing operation could not be determined.

Instead, a vacuum compatible, compact ECDL prototype for the 689 nm strontium transition has been set up (using a VPSL0690-035-X5A diode from BlueSky Research) and provided for thermal cycling tests at CSEM (see WP 5).

Deliverable D2.3 "Advanced Frequency Combs"

D2.5 (internal deliverable number): "Report on accuracy limit for multi-amplifier design and results of comparison of different fibre based frequency combs, first run" (by Menlo)

Within the first year of the SOC2 project, towards the goal of high-accuracy frequency combs, a frequency comb has been stabilized to an ultrastable laser, achieving a short-term instability of 3 x 10^{-15}. This is an important step for reducing significantly the integration times necessary to be able to measure at the 10^{-17} level.

Comparing two outputs of the same frequency comb, a stability of the beat note difference against a stable cw laser of below 2 x 10^{-19} in 10000 s could be observed. Furthermore, a frequency comb laser output has been compared with an EDFA output seeded by the same cw laser with an evaluated stability of 2.2 x 10^{-18} in 30 000 s. Finally, the accuracy of two independent optically locked frequency combs could be measured to 8.2 x 10^{-18}.

D2.11 (internal deliverable number): "Report on micro-combs performance; phase noise results from Micro-combs" (by EPFL)

During the duration of the project EPFL has managed to fabricate crystalline microresonators with sufficiently high quality factors as to allow for hyper-parametric oscillations to occur at a relatively low pump power threshold. Due to the - for microresonator based combs - comparatively low achieved repetition rates ranging from 35 to 110 GHz, it was possible to directly detect the repetition rate beat note of the resonator. The phase noise was characterized by observing the beat note between a narrow bandwidth CW laser and individual optical frequency comb lines. A broadening of the beat note, which is a measure of the phase noise present, was observed for both the directly detected repetition rate as well as the CW-sideband beat notes. The beat notes were narrow for just-above-threshold oscillation of a small number of sidebands and finally broadened to the width of the resonance.

EPFL obtained a complete understanding of the phase noise of the frequency combs generated in crystalline resonators. This understanding is not only based on experimental observations but has been combined with detailed analytic description and numerical modelling. The theoretical analysis is in excellent agreement with the experiment and allowed to derive guidelines for the design of future resonator systems.

Via comparison with other microresonator systems that have been fabricated at EPFL, such as on-chip fused silica and silicon nitride based platforms, it was found that the phase noise generating processes identified in the crystalline system are generic and apply to all microresonator based comb generators, which is also supported by the theoretical description. It was moreover experimentally shown that in certain cases careful detuning of the pump laser allows to reach low noise frequency comb states and to achieve phase locking, that is all modes are phase-coherently coupled. This work has been published in Nature Photonics **6**, 480 (2012).

For practical applications it is important to reach low phase noise states in a microresonator based comb generator on a reliable and routine basis. In laser-based frequency comb generators this is usually achieved via passive mode-locking, which always requires introducing a saturable absorber into the laser cavity. So far, however, mode-locking in microresonator based comb generators had not been shown.

Motivated by the technological importance and implications of microresonator mode-locking, EPFL investigated several schemes of mode-locking, including graphene-based saturable absorbers. Surprising from a mode-locked laser perspective it was discovered that mode-locking in microresonators can be achieved without a saturable absorber via soliton formation. This mode-locking led to the direct generation of femto-second pulses in the continuously driven micro-resonator and to the emergence of low phase noise frequency comb spectra. A special initial laser detuning sequence is required to reach the mode-locked regime. Once the mode-locked state is reached the system remains self-locked, which warrants stable long-term operation. The generation of low phase noise frequency combs via soliton-mode-locking was reported in more detail in a recent arXiv publication: arXiv:1211.0733 (2012).

D2.14 (internal deliverable number) "Report on comparison of different frequency combs, second run; report on space-related issues of fiber-based frequency combs"

Characterizations were done on two types of systems: modified "standard" Er:fiber femtosecond frequency comb (see A) and the newly-developed "figure-9" design (see B).

A. Stability and accuracy of optically locked commercial frequency combs

The combs used in this work are commercially available from Menlo Systems and come on an easily transportable breadboard, are fully automated, hands-off and with network control software. Specifications for the commercial combs in terms of stability and accuracy are at the 10^{-14} level. In the course of this work package, existing frequency combs have been evaluated to determine the operating conditions and components allowing to reach the 10^{-17} level and beyond. Necessary changes and refinements of the system hardware have been implemented in order to achieve this accuracy, namely realization of high bandwidth locking of the frequency comb to an ultra-stable CW laser which is in turn locked to a high finesse cavity. An intra-cavity EOM is used to increase the bandwidth for the repetition rate lock. In this way a 1 Hz line width frequency comb with a stability of 3 x 10^{-15} in 1 sec. has been achieved (see fig. 7). Long term operation has been investigated.
The repetition rates of two independent optical frequency combs have been optically locked at 1542 nm against an ULE-cavity stabilized laser. Their respective CEO frequencies have been locked in the RF domain. A beat note at 1150 nm has been measured with a Pi-type frequency counter between the two frequency combs. The corresponding Allan Deviation is plotted in Fig 2.6. It is remarkable that the level of 1x 10^{-17} is already reached after approx. 100 sec integration time. The level of $1\mathrm{x}10^{-18}$ is reached at about 2 000 sec.

From these measurements we conclude that the frequency combs that are currently available from Menlo Systems and that are used in many optical clock laboratories around the world are already today sufficient to allow optical clock comparison on or below the $1\mathrm{x}10^{-18}$ level if appropriate (optical) references are used.

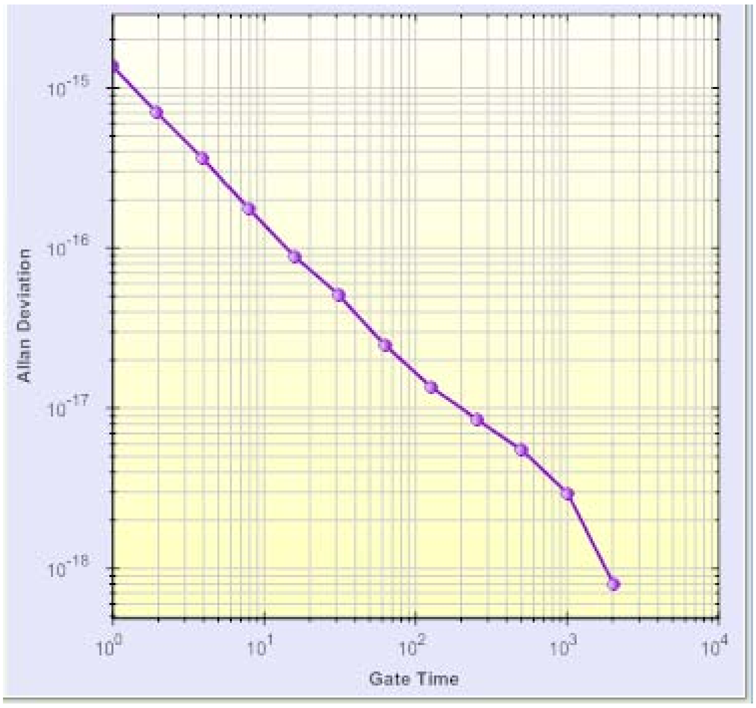


Figure 2.6: Allan Deviation of the out-of-loop beat signal (the RF beat between the two combs near 1150 nm) of two independent OFC systems. The repetition rate of each comb was stabilized by locking one comb line to an ultrastable 1542 nm laser.

B. Comparison between improved combs - second run

The above analysis of frequency combs clearly indicated that an ever increased accuracy and stability beyond what was demonstrated up to this time will require better control on the CEO degree of freedom. A laser which is inherently low noise will certainly be benefitial for this.

In line with D2.14 of the SOC II project, we have thus developed a new generation of Erbium-doped fiber based frequency combs with unprecedented stability and accuracy. The combs are still operating in the 1.5 µm spectral range. In contrast to the previous design, they use all polarization maintaining (PM) fiber and a nonlinear amplifying loop mirror (NALM) for mode locking. This technology adapted to the needs of our fiber lasers and our optical frequency combs has quickly become well-known as the Menlo Figure-9® design. The large comb mode spacing of 250 MHz is favorable for low noise applications and has not been changed.
In contrast to the previous work, a novel orthogonalized electro optic actuators now allows for a control bandwidth larger than 1 MHz for both the optical lock of one comb mode to a reference laser and for the carrier-envelope-offset (CEO) frequency lock. To assess and optimize the performance, both phase-lock loops have been analyzed using independent signal paths for locking (in-loop) and detection (out-of-loop). As shown in Fig. 2.7, an integrated phase noise below 70 mrad (100 Hz – 2 MHz) has been demonstrated for both stabilized frequencies. These two signals exhibit an Allan deviation below 10^{-16} at 1 s, averaging down to the 10^{-19} range at 1000 s. The modified Allan deviation even reaches 3 x 10^{-18} within 1 s.

Again, a comb comparison was performed in order to allow for a full evaluation of both short- and long-term performances of optical frequency combs. Therefore, we have built and compared two basically identical systems. Both systems have been installed on a water-cooled base plate to minimize temperature drifts and fluctuations. The comb spectra have been optically referenced to the same 1542 nm high-finesse-cavity stabilized CW-laser (whose ADEV is a few 1 x 10^{-15} at 1 s) using the same mode number for both frequency combs, effectively equalizing the two oscillators' repetition rate.

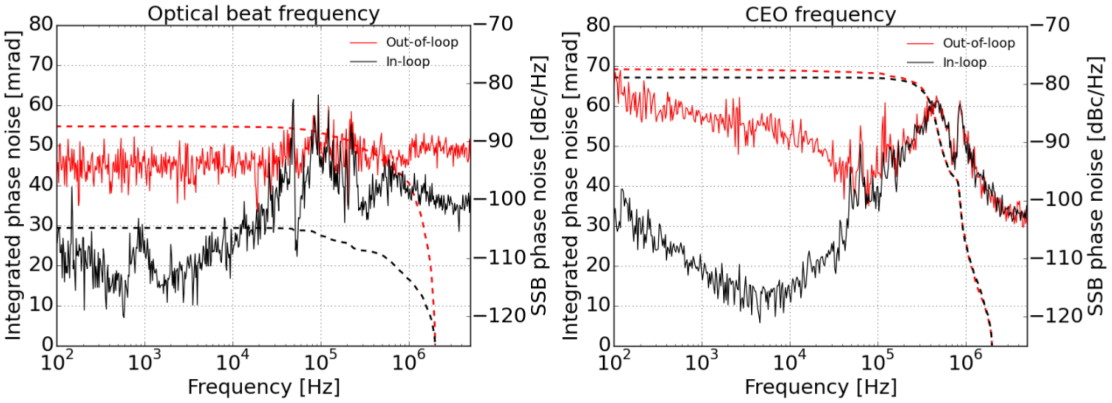


Figure 2.7: **Left:** In-loop (black) and out-of-loop (red) phase noise of the beat between a stable cw laser and one comb mode, solid lines (right scale): power spectral density, dashed lines (left scale): integrated phase noise from 2 MHz down to 100 Hz. **Right:** In-loop (black) and out-of-loop (red) phase noise of the offset frequency, solid lines (right scale): power spectral density, dashed lines (left scale): integrated phase noise from 2 MHz down to 100 Hz.

The setup is depicted in Fig. 2.8. The offset frequencies of the two combs have been locked to 35 MHz and 45 MHz, respectively, and the two combs have been compared via a direct beat signal at a wavelength of 1063.5 nm. More precisely, the comparison has been done between two frequency-doubled 2127 nm components present in the respective f-2f interferometer lights. The corresponding beat signal f_{cc} has an average frequency of 20 MHz ($2f_{ceo,2}$ - $2f_{ceo,1}$) and has been evaluated by phase noise measurements and counter-based measurements with Lambda- and Pi-type dead-time free counters.

In the direct comparison, the integrated phase noise of the comb–comb beat has been below 80 mrad (100 Hz–2 MHz). The overlapping ADEV is better than 1 x 10^{-16} at 1 s, dropping below 10^{-18} at 500 s (see Fig. 2.9). This performance is superiour to what has been target in the SOC II project and will allow a convenient and fast evaluation of optical clocks and their systematic effects.

Another interesting way to look at the stability is by tracking the phase evolution of the optical field. Over the course of more than two days of measurement, we have not encountered a single cycle slip and the overall phase excursion remained within +/- 5 cycles at an optical frequency of ~282 THz. Although we have observed a day-night variation of the optical phase due to temperature changes in our lab, the overall phase after 50 hours (or 180 000 s) is approximately within one optical cycle, allowing for a measurement accuracy of 2 x 10^{-20}.

Milestone 13 "Frequency combs able to measure the developed optical clocks at a level of 10^{-17} or better" has been achieved.

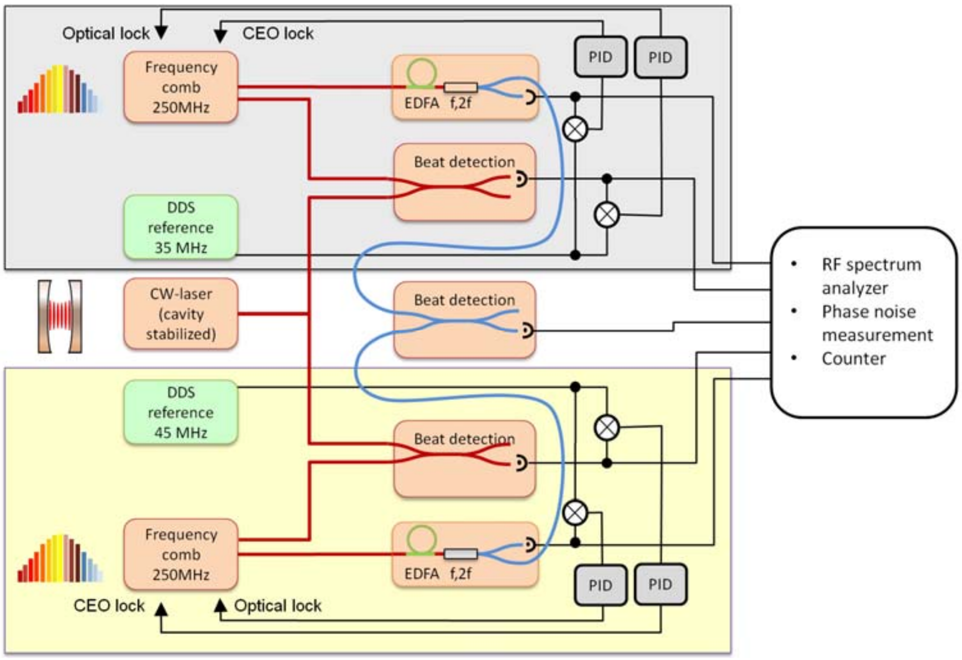


Figure 2.8: Setup for the figure-9 comb-comb comparison. Two frequency combs are locked to the same 1542 nm CW reference laser (left side, middle). The stabilization scheme is chosen such that the two optical frequency combs are offset by 10 MHz, sharing the same repetition rate. Temporally overlapping the two pulse trains on a photodiode, we observe the corresponding beat signal (center, middle).

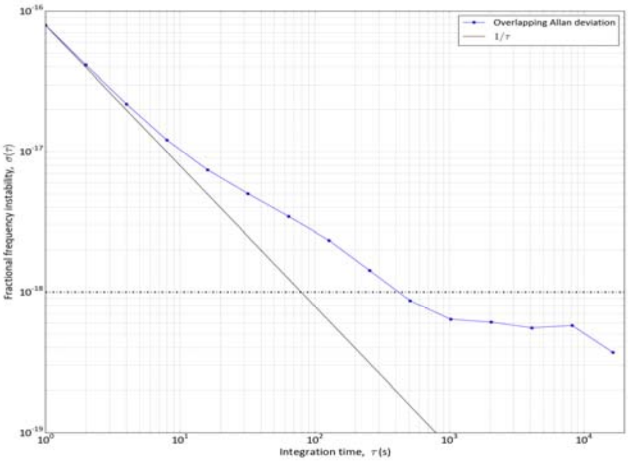


Figure 2.8: ADEV of figure-9 comb comparison, with the beat performed at 1064 nm.

Work package: **WP3: Atomics Packages**

WP 3.1 and WP 3.2

(UDUS) Within the first two years, the atomics package for the transportable Yb optical lattice clock had been completed and it was demonstrated that (1-2) x 10^6 ^{171}Yb atoms at temperatures of 20-30 µK could be prepared in in the postcooling MOT.

Milestone 14 has been partially completed.

Continuous improvements to the system are made regarding the laser system (see WP 2) and the overall layout in order to simplify transportability (see WP 4). For example, a new laser system for the generation of 399 nm radiation had been installed and currently the vacuum setup is completely overhauled including the installation of a new enhancement resonator setup. These improvements are described in detail in the reports on WP2 and WP4.

Milestone 15, 20, and 21 have been completed with modifications.

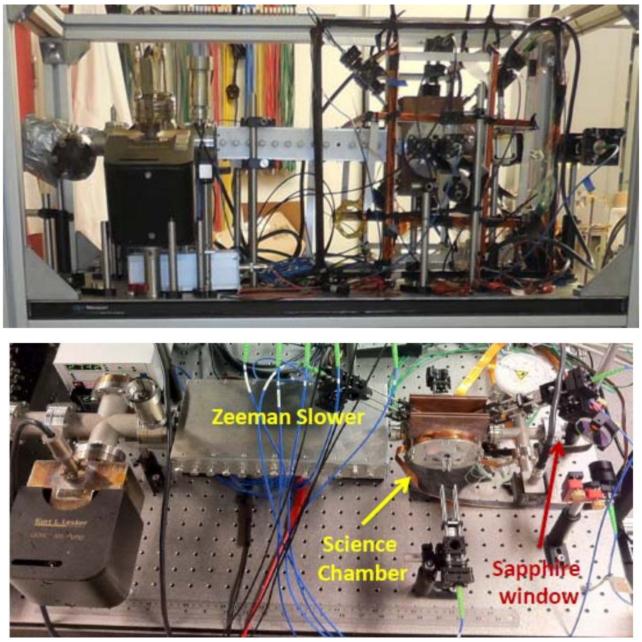


Figure 3.1: Side and top views of the 2nd generation Sr atomics package, showing the compactness of the MOT ("Science") chamber (right). The permanent-magnet Zeeman slower is at the center.

WP 3.3

(**NPL**) In the first two years of the project, a novel design of a Sr optical lattice clock vacuum chamber with well-controlled temperature environment has been conceptually developed and finalized. The design goal was to provide an environment in which blackbody radiation shifts (BBR) can be measured accurately.

(**UOB**) A compact MOT chamber with seals was designed, constructed and been put into operation (Figure 3.1). The vacuum chamber was then incorporated in the Sr 2nd generation apparatus (see WP 4 for final performance). The constructed chamber is indeed very compact and lightweight.

Milestone 18 has been achieved.

(**INRIM**) A new design concept for a compact vacuum system for an Yb optical lattice clock which had been developed during the first two years of the project has been setup and put into operation (in a stationary Yb optical clock apparatus at INRIM) in the third year. A scheme of the new vacuum chamber is shown in Figure 3.1. The key concepts of this design are:

- Compactness and low electrical consumption;
- Vacuum high performance;
- Cold atoms loading without Zeeman slower
- Mitigation of the Blackbody Radiation shift uncertainty.

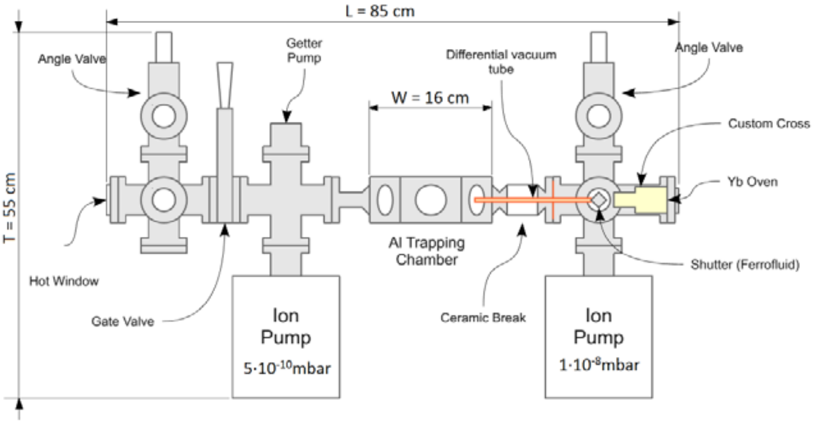


Figure 3.2: Schematic drawing of the new compact vacuum apparatus for Yb

The setup is 85 cm long, and the main feature is the absence of a Zeeman slower. The ultra-high vacuum is guaranteed by two ion pumps, a getter pump for hydrogen. The MOT chamber is made out of Aluminum ensuring a lightweight design and minimum degasing. The windows are sealed on the Al chamber using indium gaskets, to obtain a large optical access to the chamber itself. The MOT magnetic coils for the SOC2 setup have a power consumption < 15 W, so that water cooling is not necessarily required. In Figures 3.3 and 3.4 several views of the set up are presented.

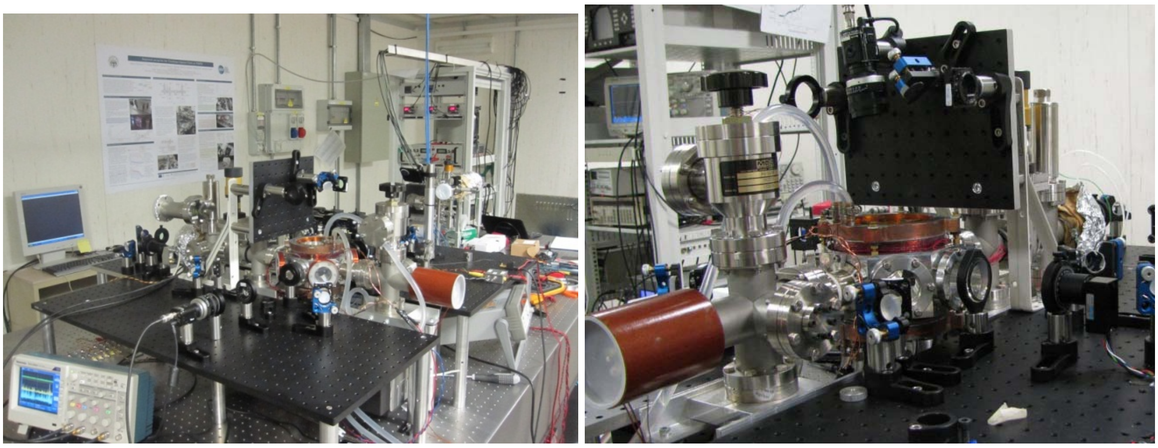


Figure 3.3: The new compact vacuum apparatus for Yb.

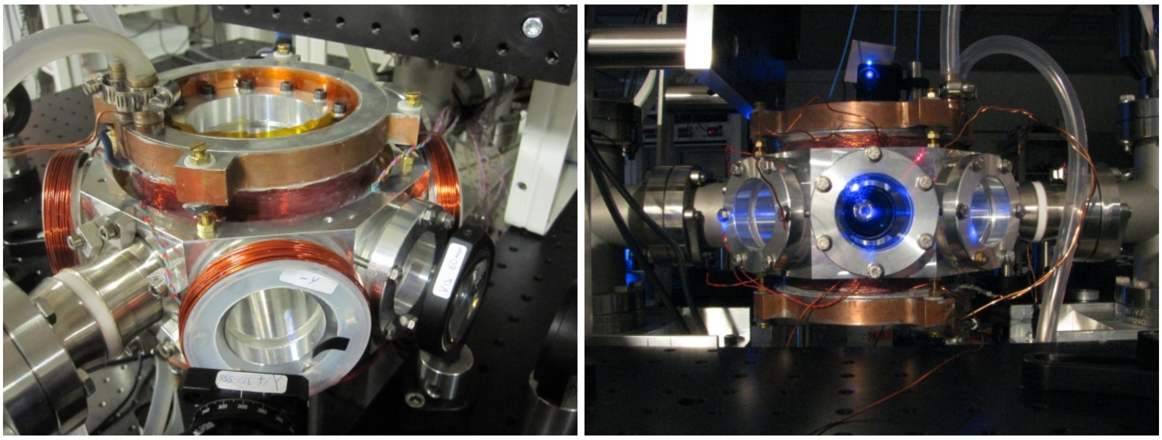


Figure 3.4: Main chamber of the new compact vacuum apparatus for Yb.

In the stationary version of the new compact clock apparatus, loading of an Yb MOT without a Zeeman slower has been optimized (see below).

In addition to the vacuum chamber for the stationary (compact) setup at INRIM, a similar chamber has been built that will be used for a next generation transportable Yb system. As in the transportable apparatus at UDUS the optical lattice for trapping of the atoms will be created in an optical enhancement resonator which is located inside the vacuum system. A design of this resonator adapted to the new compact system has been developed and is currently being built (see Figure 3.5).

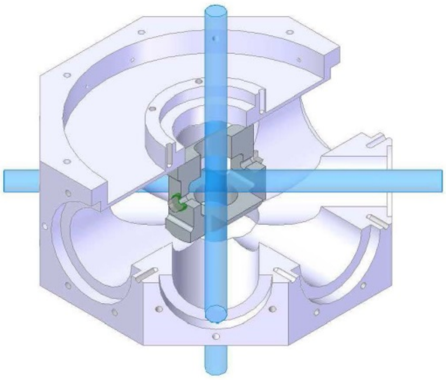


Figure 3.5: Schematic drawing of the enhancement resonator inside the new compact vacuum chamber.

Milestone 19-part a has been completed.

WP 3.4

(NPL) Within the first two years of the project, a spin-flip slower for Sr which uses permanent magnets [Ovchinnikov2008] has been designed and built. It had been demonstrated that a precooling MOT could be loaded from the permanent-magnet slower with ~ 4 x 10^8 atoms within 0.5 s.

Milestone 16 has been achieved.

(UOB) 2D/3D MOT atomics apparatus

Already in the first year of the project, preliminary results on loading of a 3D MOT for Sr from a 2D MOT had been achieved. However, no further significant improvements using the system performance could be obtained. Therefore, we have launched an effort to optimize the 2D MOT by carrying out further simulations for the 1D situation.

We use a semi-classical approach where an atom interacts with two counter-propagating plane waves. As a result of the interaction, it undergoes cycles of absorption and emission. Assuming spontaneous emission, in the entire cycle, the net average momentum transfer to the atom is equal to the absorbed photon's momentum. Using this technique, one can cool the atom whilst trapping is carried out by using additional magnetic field. The average acceleration (or force) on the atom depends on parameters such as detuning δ, intensity of the laser I and the linewidth of the cooling transition. For Sr, the linewidth of the first stage cooling transition ($^1S_0$-$^1P_1$) is approx. 31 MHz. In addition to the above mentioned parameters, different geometries for the dispenser positions have been included in the simulations. Below, with regard to the dispenser, we compare two different geometries, assuming that the dispenser has no angular spread:

1) Ejection of atoms is along the zero magnetic field line of a 2D MOT (Figure 3.6, left).
2) Ejection of atoms is perpendicular to zero magnetic field line of the 2D MOT (Fig. 3.6, right).

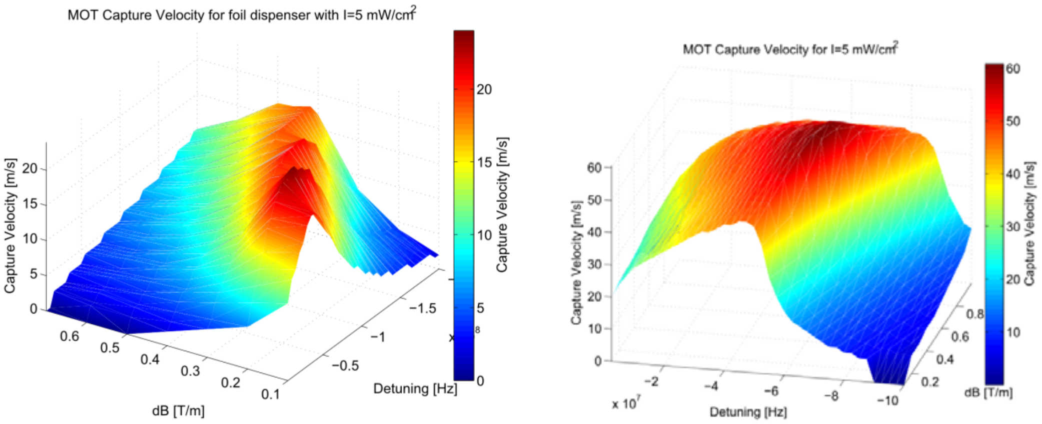


Figure 3.6: (left) Ejection of atoms along the zero magnetic field line of a 2D MOT, the maximum capture velocity is approximately 20 m/s. (right) Ejection of atoms is perpendicular to the zero magnetic field line of a 2D MOT, the maximum capture velocity is approximately 60 m/s.

The simulations clearly show a strong dependence on the geometry of the dispenser position. For exactly the same parameters, the dispenser with the ejection of atoms perpendicular to the zero magnetic field line has a 3 times higher capture velocity in the 2D MOT as compared to the case when the ejection of the atoms is along the zero magnetic field line. The factor of 3 in capture velocity translates into approx. a factor of 1000 in atom number. For example, if we increase the intensity per laser beam to 150mW, an increase of the cold atom flux increases from 3 x 10^6 atom/s to ~10^9 atom/s is expected. It is worth noticing that the latter flux is very similar to that obtained with a Zeeman slower.

As a result of the above simulations, we have set up a completely new 2D MOT facility (Figure 3.7) in which the dispenser is mounted such that the ejection of atoms is perpendicular to the zero magnetic field line. This is done in order to minimize the velocity component of atoms along the trapping axis. The new setup 2D MOT chamber is formed by an 8 way cross with six CF-35 tubes and two CF-16 tubes which are used to mount two separate dispensers. 4 ports out of the six CF-35 ports, are used for the 2DMOT laser beams while the remaining two allow for a pusher beam and to couple the 2D MOT chamber with the three 3D MOT chamber. An ion pump maintains ultra-high vacuum (UHV) in the entire system. In this new system, a 3D MOT without using the 2D MOT has recently been realized and the next step is to realize the 2D MOT. Like the earlier apparatus, permanent magnets are used for the required magnetic field gradient. As compared to the old system, in the new system, magnets are closer thereby generating higher gradient (~40 G/cm) which is needed for a Sr MOT.

It is worth mentioning that in the absence of a properly optimized 2D MOT, the permanent magnet Zeeman slower from NPL has been used as the base line for the advanced atomics package, but at the same time making sure that the advanced chamber is also easily adaptable to 2D MOT configuration.

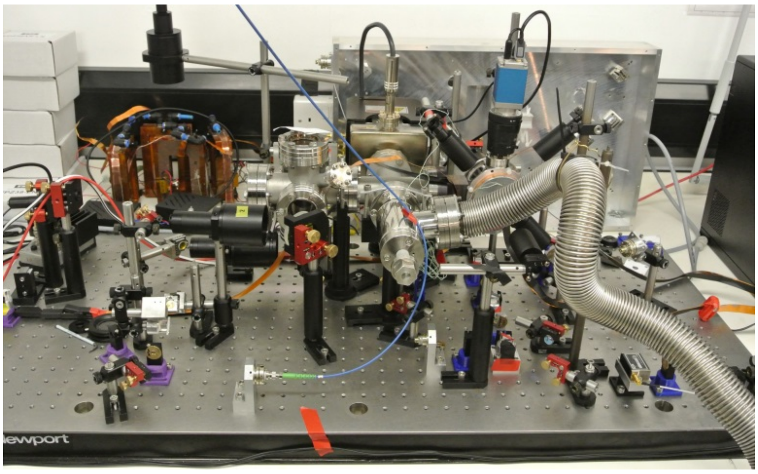


Figure 3.7: New 2D / 3D MOT assembly. Center of photo: the 2D MOT chamber is formed by a 8-way cross with six CF-35 tubes and two CF-16 tubes which are used to mount two separate dispensers. Center-right of photo: 3D MOT chamber (partially hidden by pumping line) shown with circular windows (optical telescope and camera mounted). A 25 liter/s ion pump maintains ultrahigh vacuum (UHV) in the entire system.

Milestone 17 was partially completed.

(INRIM) Yb atomics system without Zeeman slower

In the first year of the project, preliminary tests regarding the possibility to load an Yb MOT from an atomic beam without the use of a dedicated Zeeman slower had been performed and up to 4 x 10^5 atoms were loaded into a precooling MOT. In the new compact vacuum system the concept of loading has been experimentally optimized and loading of a precooling MOT with more than 10^7 atoms for several Yb isotopes could be demonstrated. The experimental investigations were supported by simulations indicating that with 20 mW in the slowing beam, capture rates of up to 8 x 10^8 atoms/s could be possible for ^{171}Yb.

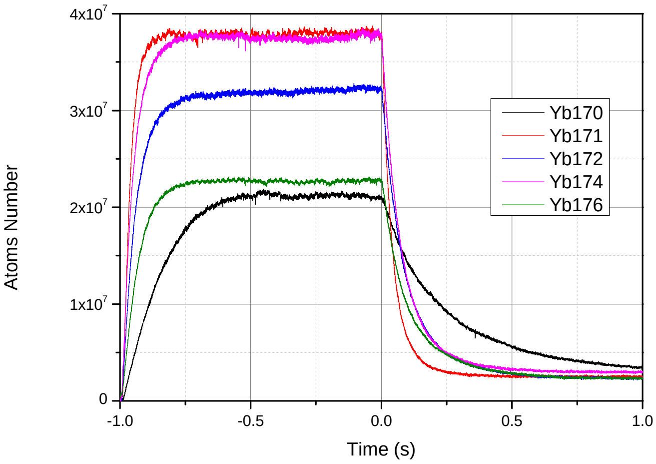


Figure 3.8: Loading and decay curves for different Yb isotopes. The decay is induced by switching off the pre-slower laser beam.

For efficient slowing without a dedicated Zeeman slower, a laser beam at a wavelength of 399 nm counter-propagating with the atomic beam is still required but instead of a dedicated Zeeman slower magnetic field coil, the fringe field of the MOT magnetic coil is used for slowing. Figure 3.8 shows the loading process in this configuration for 5 different Yb isotopes: 3.8×10^7 atoms of ^{171}Yb or ^{174}Yb were loaded in 130 ms, while we are able to trap 3.2×10^7 ^{172}Yb atoms and 2.2×10^7 atoms of ^{170}Yb or ^{176}Yb.

In Figure 3.8 we report also the trap emptying after switching off the pre-slower laser beam.

The maximum obtained capture rate is 3×10^8 atoms/s for ^{171}Yb. This result is reasonable agreement with the simulated value of 8×10^8 atoms/s. The pre-slowing enhances the number of trapped atoms by a factor of 15. The atoms, loaded in the 399 nm MOT are subsequently transferred to the 556 nm MOT with 80% efficiency.

In Figure 3.8, the pre-slower power beam had a power of 50 mW, with 1 cm diameter. Figure 3.9 shows the loading behavior of the MOT as a function of pre-slowing power. We observe a threshold around 25 mW, where the atoms number is reduced to ~20% the maximum value. Nevertheless, even down to 5 mW, the number of trapped atoms is 4×10^6, and could be increased by increasing the oven temperature, currently kept at 400 °C. Even under these conditions, the atoms number is enough for Yb clock operation within the SOC2 targets.

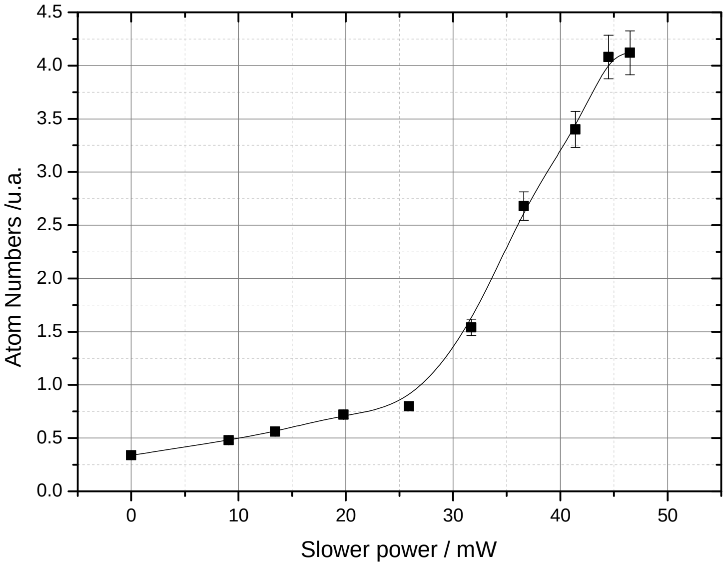


Figure 3.9: Atom number in the MOT as a function of laser power in the pre-slowing beam.

As mentioned, the pre-slowing process involves the MOT stray magnetic field, so that a short Zeeman slower effect is exploited. This is evident because the pre-slower polarization is a relevant parameter, and due to the Zeeman splitting, a circular polarization enhances the loading gain. The pre-slower frequency is red-detuned with respect to the resonance, with a maximum for loaded atoms around -346 MHz, and ~45 G/cm for the magnetic field gradient at the center of the MOT. Figure 3.10 shows the atom number in the MOT as a function of pre-slower detuning and current through the MOT coils.

Milestone 19-part b has been completed.

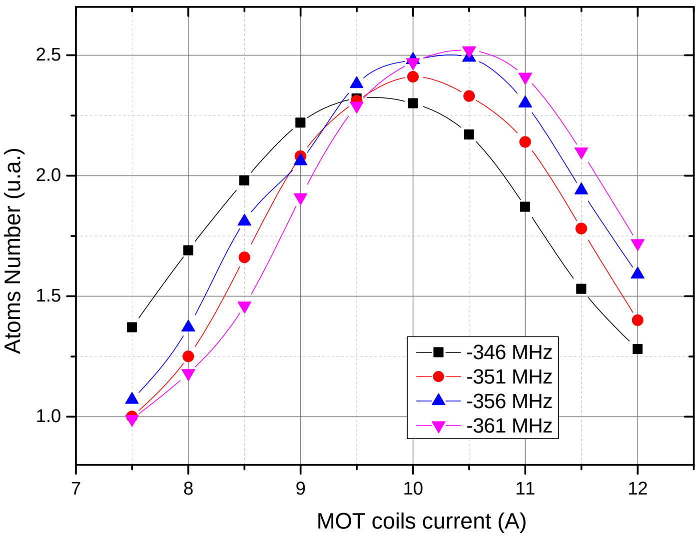


Figure 3.10: MOT atom number as a function of MOT coil current and pre-slower detuning.

Work package: **WP4: "Integration and characterization of clock demonstrators"**

WP4.1 Advanced Strontium clock integration and optimization

At the Università degli Studi di Firenze (UNIFI) a first-generation atomics package has been developed. In the course of this project it underwent preliminary characterization and optimization. Later, compact laser distribution breadboards and frequency stabilization system (FSS) developed mainly by TOPTICA, PTB, HHUD and NPL were transferred to UNIFI and combined with the atomics package. After a first test on the complete laser system (second-year WP4 report) the clock has been tested for stability, accuracy and reliability.

The stability of the Sr clock was evaluated using a 642 km optical fiber link that since May 2013 connects the Italian metrological institute (INRIM, located in Torino) to UNIFI. By the link, INRIM disseminates the signal from its cryogenic Cs fountain.

The system at UNIFI consists of a high-power 461 nm laser source, a 813 nm trapping laser, two repumpers laser at 707 nm and 679 nm (all laser diodes done by TOPTICA), a compact frequency distribution breadboard for 461 nm radiation, and a compact vacuum apparatus for trapping and cooling Sr isotopes. The sub-systems that have been integrated and tested at UNIFI are: the second stage cooling laser at 689 nm from PTB, with TOPTICA control electronics and locking electronics from Heinrich-Heine-Universität Düsseldorf (UDUS); the clock laser at 698 nm also from PTB and TOPTICA, the stirring laser for ^{87}Sr realized at PTB with TOPTICA control electronics and locking electronics made at PTB; and the Frequency Stabilization System (FSS) realized by NPL and UDUS. The apparatus produces around 10^4 88Sr atoms at µK temperatures in the optical lattice in ~300 ms.

The 698nm laser linewidth has also been tested with a stationary clock laser at 698 nm developed at UNIFI. The ~1Hz beat note linewidth is consistent with the two laser instabilities. The PTB clock laser has then integrated with the atomic system. The laser is pre-stabilized with a high-finesse transportable cavity from PTB. The probe light, resonant with the 1S0-3P0 clock transition in 88Sr, is amplitude stabilized to 1% level.

This stabilization has become necessary due to observed slave laser injection instabilities due to alignment changes on a daily basis. Changes of the output power (more than 30% of the total power) from the master laser were also observed on a daily basis.

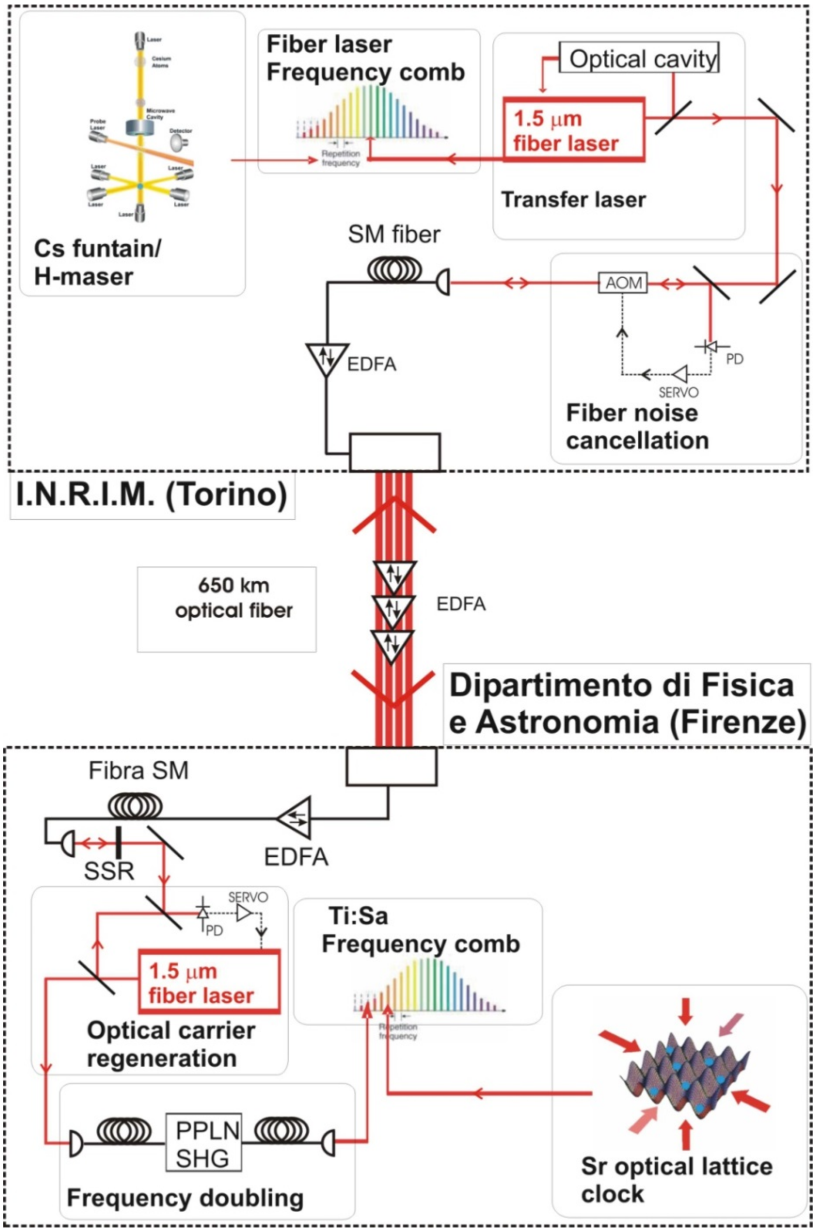


Figure 4.1: Experimental setup for the absolute frequency measurements of the Sr clock at UNIFI with respect to Cs fountains at INRIM through the 642 km coherent optical fiber link.

Due to the unavailability of an independent stationary clock at UNIFI for the characterization of the stability of the SOC2 Sr clock, we took advantage of a recently developed 642 km fiber link from INRIM to UNIFI that transfers the Cs fountains clock references held at INRIM.

Figure 4.1 illustrates the experimental setup employed in the remote absolute frequency measurement. The optical link is based on a 1.5 μm transfer laser, locked to an ultra-low expansion (ULE) high finesse cavity, calibrated by a fiber-based optical frequency comb (OFC) referenced to the H-maser and Cs Fountains. The transfer laser light is sent through the 642-km-long optical fiber to UNIFI, provided by the Italian Research & Education Network (GARR), connecting Torino to Milano, Bologna and Firenze with a total loss of about 172 dB. Nine bidirectional Erbium-doped Fiber Amplifiers (EDFA) were installed along the fiber haul to compensate the signal losses. A part of the laser radiation at UNIFI is looped back to INRIM and it is used to compensate the phase noise added by the fiber itself. In this way, the contribution to the transfer stability was evaluated at $1 \times 10^{-14}/\tau$, where τ is the integration time.

In Firenze, a local laser (External Cavity Laser, RIO Planex) is phase-locked to the signal coming from Torino. The UNIFI laser is then frequency-doubled (to produce 771 nm radiation) in a periodically-poled LiNbO3 waveguide and sent to the UNIFI Ti:sapphire-based OFC together with clock laser (698 nm) light, referenced to the ^{88}Sr $^1S_0$-$^3P_0$ transition. The Sr lattice clock located in Florence is then measured with respect to the 1.5 µm transfer laser which is, at the same time, calibrated with respect to an H-maser and a Cs fountain in Torino.

The stability of the absolute measurement of the Sr clock with respect to the fountain is shown in Fig. 4.2 and it is limited by the H-Maser stability. Nevertheless, this stability demonstrates that the 1st generation demonstrator is able to achieve a stability better then 1E-15 in 1000 s, and there are no evident problems in the Sr clock stability at this level. In spite of the good medium-term stability, the absolute measurements of the Sr clock transition frequency reported an offset with the CIPM accepted value of about 20 Hz.

The assessment of the main biases of the Sr clock has shown inconsistent individual measurements of the AC stark shift from the lattice laser. Further measurements should have been devoted to this problem, but the transfer of the laser system to UOB that needed to take place in October 2014 prevented this.

Milestone 22 “Full characterization results of compact and transportable 1st generation Sr clock” is partially achieved.

Deliverable 4.1 “First Sr clock demonstrator” has been submitted, resulting also in a publication:

N. Poli, M. Schioppo, S. Vogt, S. Falke, U. Sterr, C. Lisdat, G. M. Tino,
“A transportable strontium optical lattice clock”,
Applied Physics B: 117 (2014) 1107 – 1116; dx.doi.org/10.1007/s00340-014-5932-9

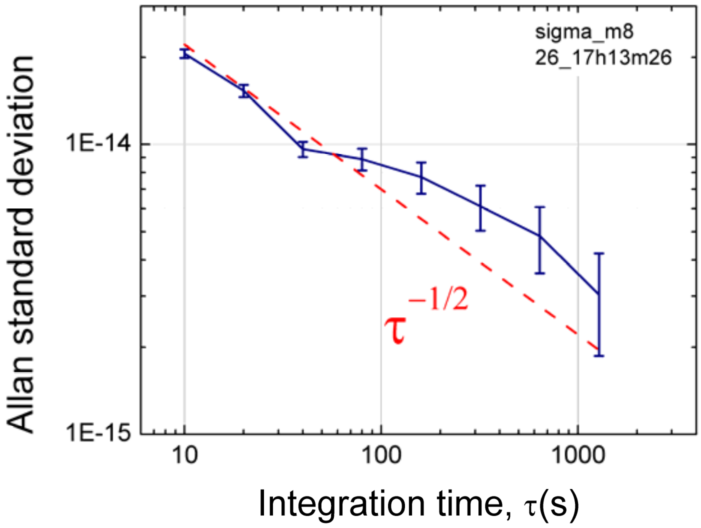


Figure 4.2: Allan standard deviation of the absolute frequency measurement of the Sr clock versus the Cs fountain (blue, solid) and the expected $\tau^{-1/2}$ from the fountain stability (red, dashed).

WP 4.3 and 4.4 Advanced Sr clock integration and optimization; Clock optimization II and full characterization with respect to stationary clocks

Here the task has been to integrate two demonstrators, the 2nd generation Sr system and the Yb system, their first evaluation, their transportation to the metrological institutes INRIM (Yb clock) and PTB (Sr clock) and the work done at the metrological laboratory towards the evaluation of the ultimate performances.

The integration of the two systems is completed, and the transportation to the metrological institutes was successful. At the end of the project, both apparata are operational, but are not yet operating as clocks. The Yb demonstrator was preliminarily characterized before transportation.

At the metrological institutes, the detailed metrological characterization of both systems has not started yet, because of various reasons: technical problems in the demonstrators' subsystems, non-ideal environmental conditions in the metrological institutes, the large time effort required to achieve stable operation, a requirement for initiating detailed characterizations.

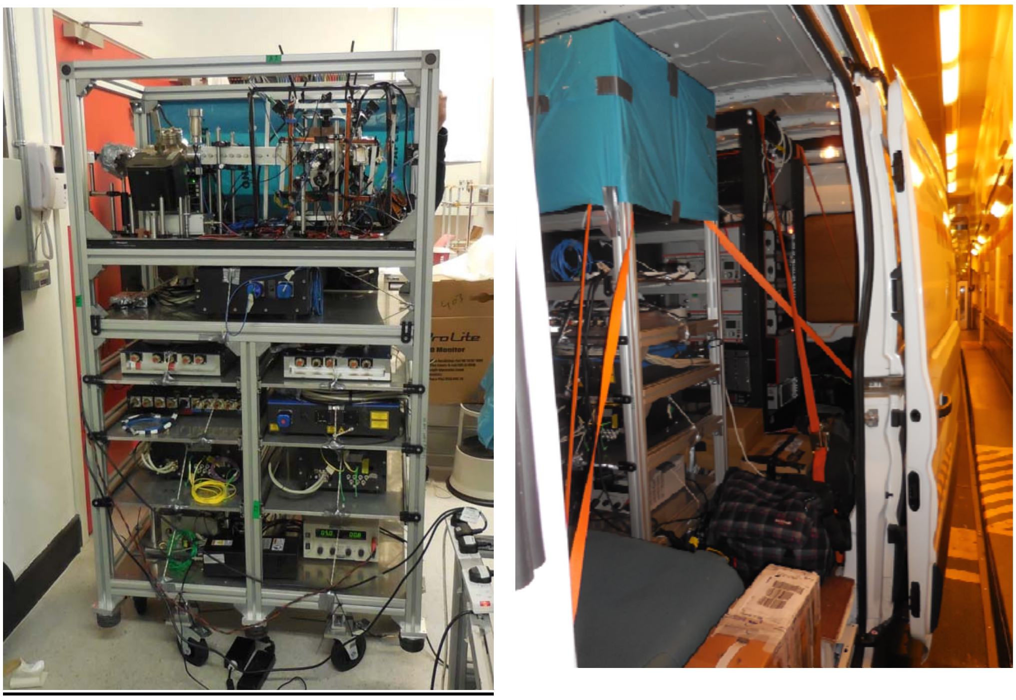


Figure 4.3 The Sr 2nd generation system in the lab (left, without electronics rack and clock laser subsystem) and on the Eurotunnel train on its way from UBham to PTB (right).

Deliverable D4.3 "Final Sr clock demonstrator"

The Sr demonstrator has been moved from University of Birmingham to PTB in mid-2015 for completing the atomic sample generation and the clock operation.

The move, which occurred by van (Figure 4.3), went very well. The 1st stage MOT was obtained within 2 days of arrival. Atoms were trapped in the lattice within 3 weeks of arrival. The clock transition was first observed in December 2015, after integration of the SOC clock laser whose cavity was transported from SYRTE to PTB (Figure 4.4.).

The apparatus works well: in one test, it ran continuously for 24 hours without loss of laser lock. After this interval and a minor readjustment of the repumper lasers' frequencies, the clock transition was immediately observed (1 min after manual initiation).

Currently, the best result is the observation of the transition linewidth in ^{88}Sr with 9 Hz FWHM using the SOC clock laser stabilized additionally to a very stable reference laser (Figure 4.5).

When the SOC clock laser is used as is, the transition linewidth is approximately 50 Hz wide. The reason is the performance of the SOC clock laser, which is currently not up to specification, because of non-ideal vacuum conditions in the reference cavity chamber. The current Allan deviation is $1\text{x}10^{-14}$, while the goal value is $5\text{x}10^{-16}$.

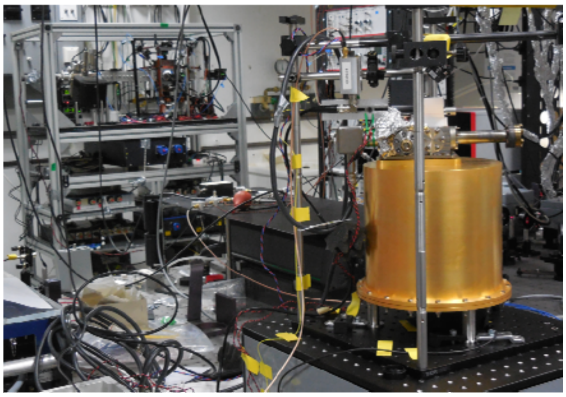


Figure 4.4: The SOC2 2nd generation Sr demonstrator installed at PTB. In the foreground the vacuum chamber of the clock laser cavity. In the left background the rack with the atomics package and the cooling lasers.

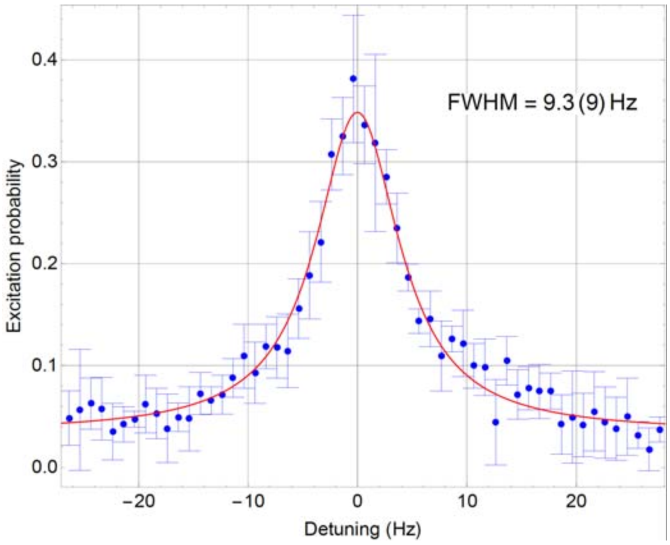


Figure 4.5: Clock transition of ^{88}Sr in the SOC apparatus, in a 1D optical lattice. The SOC clock laser was prestabilized to the SOC reference cavity and then its frequency was locked to the stationary PTB reference clock laser. This enabled reducing the linewidth of the SOC clock laser significantly.

Milestone 28 has been achieved.

After the end of the SOC2 project, the development of the Sr demonstrator is ongoing with full effort keeping the system at PTB. A first evaluation of accuracy and stability is expected by mid-2016, while the goal performance originally set for the project will likely require until mid-2017.

Concerning **Milestone 25** ("Full characterization of Sr clock demonstrator concerning uncertainty and stability"), we can state partial achievement: We expect that the system can indeed reach a high stability, because the clock transition is observed with ultra-narrow linewidth (9 Hz), an essential requirement.

Towards the goal of reaching an inaccuracy below 1x10^{-16} (**Milestone 29**) we have made an analysis of how to control the black-body shift caused by the atomic chamber. The necessary hardware modifications (calibrated temperature sensors and active temperature control using TECs) have been defined and will be implemented.

Finally, we summarize the mass and power budget of the current version of the SOC Sr breadboard in Tables 4.1 and 4.2.

Vacuum system with breadboard:	50 kg
Blue cooling laser (461 nm):	20 kg
Distribution module for blue laser:	5 kg
Red cooling and stirring laser (689 nm):	24 kg
Repumpers (707 and 679 nm):	30 kg
Lattice laser (813 nm):	30 kg
Frequency stabilization system (FSS):	25 kg
Power supplies:	30 kg
Total atomics unit (without electronics)	**214 kg**
Clock laser cavity:	9 kg
Clock laser vibration isolation unit:	28 kg
Clock laser breadboard:	20 kg
Total (without electronics)	**271 kg**
Electronics (estimated):	200 kg
Total with electronics (est.)	**471 kg**
Frequency comb FOKAL (MenloSystems):	18 kg

Table 4.1: Overview of the mass contributions to the SOC breadboard clock system as of January 2016. The total mass of the apparatus is approximately 500 kg. This number does not include the mass of the rack structure.

Clock laser:	100 W (est.)
Atomic package	
blue laser (461 nm):	145 W
repumpers (679+707 nm):	59 W
red laser (689 nm):	62 W
lattice laser (813 nm):	93 W
Frequency stabiliz. syst.:	153 W
Oven:	20 W
Amplifiers for AOMs: ca.	140 W
MOT coils:	12 W
	684 W
2 oscilloscopes,	
2 computer,	
FPGA:	200 W (est.)
stirring laser:	62 W (est.)
Frequency comb FOKAL:	65 W (a prototype of MenloSystems for airborne use)
Total	**1120 W (est.)**

Table 4.2 Estimate of power consumption, performed in part by direct measurement of consumed power

Deliverable D4.4 "Final Yb demonstrator: Full characterization of the Yb clock and comparison between the two approaches"

The clock demonstrator has been completed at the University of Düsseldorf (HHUD) and transported to INRIM in Italy in order to compare it to the primary standard, the cryogenic Cs fountain and to the stationary Yb clock. Before transportation, HHUD demonstrated the operation of the clock, a linewidth of the clock transition of 12 Hz (Figure 4.6) and a stability of 5 x 10^{-15} (for integration times > 100 s) (Figures 4.7, 4.8) using an H-maser as a reference. The characterization included studies of the influence of the wavelength of the optical lattice, the Zeeman shift and the DC Stark shift.

Milestones 23, 26 have therefore been partially achieved.

While the clock has been transported successfully to INRIM and put back into operation within a couple of days, a comparison with the atomic frequency standards at INRIM and therefore detailed studies of systematics could not be realized so far due to technical problems.

Milestone 24 "Density shift data for at least two different Yb isotopes" could therefore not be achieved. In any case, it had been redefined to focus on the fermionic isotope ^{171}Yb only.

The basic setup of the atomics package for Yb has already been described in report D3.1. Nonetheless, during the fourth year, some relevant improvement has been done, as the implementation of a new setup for the laser system at 399 nm, a new intra-vacuum resonator for the optical lattice and the integration of the repumping laser at 1388 nm into the system.

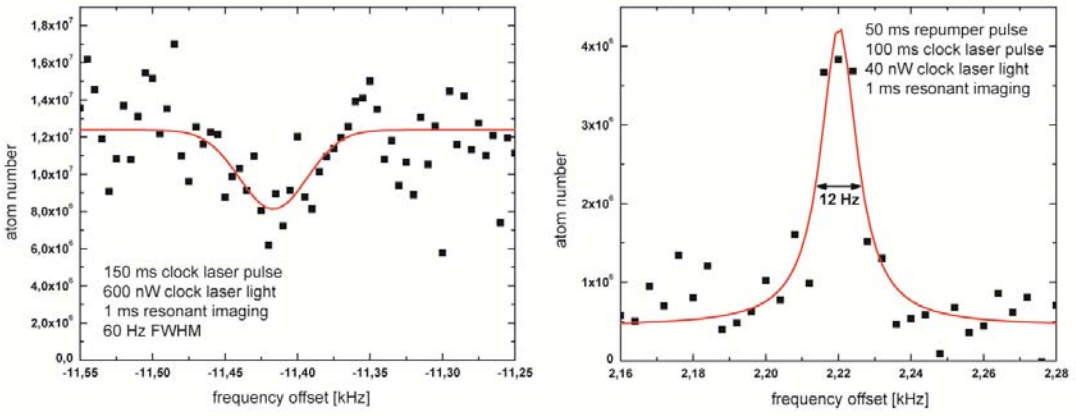


Figure 4.6: Comparison of clock spectroscopy on ^{171}Yb in a 1D optical lattice without (left) and with (right) the use of a repumping laser. Using the repumper, a linewidth as small as 12 Hz could be observed.

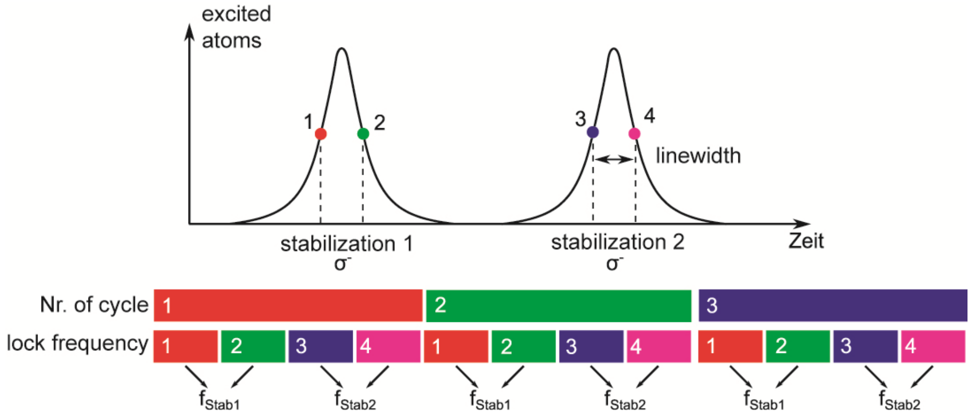
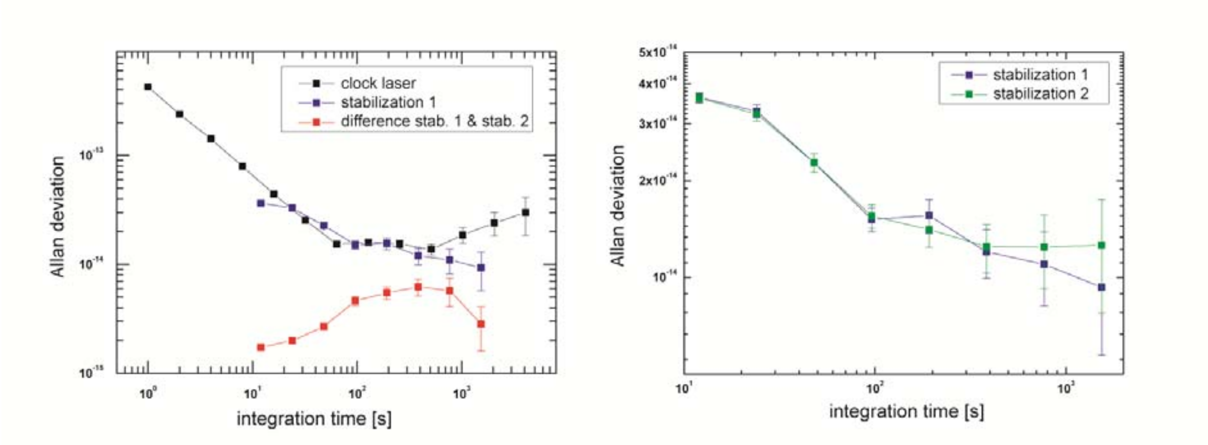


Figure 4.7: Scheme of the stabilization of the clock laser to the atomic transition. During one cycle two independent locks are realized (Lock 1 and Lock 2). The frequency for both locks is independently set using

an AOM.



a) b)

Figure 4.8: On the left, Allan Deviation for the clock laser, single lock of the clock laser to the atomic reference (stabilization 1) and for the difference of the two independent locks depicted separately on the right. For short timescales (< 100 s) the lock has essentially no effect (i. e. the gain is not large enough) and only for longer timescales an effect of the lock is visible.

The transportation at INRIM by van was successful. The characterization of the system at the new laboratory (Figure 4.9) has been prevented by technical problems with the location, the clock laser, and the atomic source. Presently, the linewidth is limited to several hundreds of hertz. The clock laser diagnostic is also empowered by the possibility of producing a beat note with the INRIM Yb clock laser as well as using the INRIM optical frequency comb locked on an IR ultrastable laser.

Most recently, the Yb clock has been moved to an own laboratory room, where it can operated more undisturbed.

Efforts are under way to bring the transportable Yb optical lattice clock back on line and conduct a complete evaluation of the system beyond the timeframe of the present project. We plan to reach an inaccuracy below $1x10^{-16}$ (**Milestone 29**) in 2017.

Milestone 27 "Full comparison of the properties of the two clocks as input for preliminary design of space clock" has been achieved. Based on the European laboratory results on stationary Sr clocks, the successful operation of the transportable and modular 2nd generation Sr system, the advances in laser technology for the cooling lasers of Sr (especially the 461 nm 1st stage cooling lasers), in 2014 the consortium in consultations with ESA decided on choosing strontium as species for the space optical clock.

Figure 4.9: The Yb clock set up in its first location at IRIM.

Workpackage: **WP5: Robustness, lifetime testing of laser diodes**

Workpackage 5 “Robustness (thermal, thermal vacuum), lifetime testing of laser diodes” was dedicated to reliability and robustness tests of selected lasers of an optical clock operated in conditions that are representative of a space environment (e.g., in terms of temperature, vacuum, radiation).

Two different types of lasers developed in SOC-2 by LUH have been characterized:

i) a **compact external cavity diode laser** (ECDL) **at 689 nm** (2nd stage cooling laser for Sr clock) in a complete set of environmental conditions including thermal-vacuum and successive exposure to gamma and protons radiations;

ii) a **fiber-coupled high-power laser at 759 nm** (lattice laser for Yb clock) in a limited set of temperature conditions.

Details are found in the **Deliverable D5.1** “Report and two tested laser modules”.

Milestone 30 “Assessment of robustness of selected lasers under space conditions” has been reached

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Work package: WP6: “Assessment of components and preliminary design and roadmap for space optical clock”

Work package 6 "Assessment of components and preliminary design and roadmap for space optical clock" contains an assessment of the criticality with respect to space application of the transportable systems/subsystems. An analysis of the SOC breadboards was be used for a definition of requirements for an optimized space clock design including the major interfaces and budgets to generate a roadmap towards space developments.

Details are found in the deliverables.

Milestone 31 “Preliminary design for a 3rd generation design/space clock and roadmap towards space qualifications” has been reached.

Impact of the project

The space mission “SOC” on the ISS

The main goal of the present project was to make a significant step towards a first prototype of a space clock, to be flown eventually on the ISS. In February 2014, the SOC consortium was asked to submit a report on its results and a roadmap for further development. The report submitted in March 2014 was accepted by ESA and “SOC” remained a mission candidate in the ELIPS program. This positive result would not have been possible without the intermediate results achieved in this project.

Through our interactions with US colleagues, we supported NASA’s ISS fundamental physics program to fund some US groups (e.g. the group of C. Oates at NIST) to conduct collaborative researches with European colleagues for the SOC project. Both the US scientists and the NASA sponsor have strong interests in international collaboration in these fundamental physics areas.

In 2016, ESA prepares the next phase of Life and Physical Science research in the ESA Human Spaceflight and Exploration programme (this is the program that uses the ISS) covering the period up to 2024. ESA called the consortia active in the ELIPS program to develop or update their roadmaps.

A roadmap update concerning the use of optical clocks in space, in particular on the ISS, was produced by the coordinator of SOC with support from the SOC consortium. It is enclosed as an appendix in the report of year 4.

On the demand of the national delegations to the programme, a Research Community Consultation Workshop open to the broad scientific community, took place at ESTEC on the 18th-20th January 2016. Here the coordinator presented the SOC project, in particular to the Human Spaceflight and Exploration Science Advisory Committee (HESAC). This committee is called to formulate recommendations to ESA as the roadmaps should become key elements of the programme starting in 2017 that will be proposed for funding at the ESA Council at Ministerial level of end of 2016.

The roadmap document was endorsed by the following scientists, mostly members of the SOC consortium:

In alphabetical order of institution acronym:

Dr. Steve Lecomte	steve.lecomte@csem.ch	CSEM	Centre Suisse de Microtechniques, Neuchâtel
Prof. Claus Braxmaier	braxm@zarm.uni-bremen.de	DLR	Deutsches Zentrum für Luft- und Raumfahrt, Bremen
Dr. Davide Calonico	davide.calonico@inrim.it	INRIM	Istituto Nazionale di Ricerca Metrologica Torino, Italy
Dr. Nan Yu	nan.yu@jpl.nasa.gov	JPL	Jet Propulsion Laboratory, Pasadena, USA
Prof. Ernst M. Rasel	rasel@iqo.uni-hannover.de	LUH	Leibniz-Universität Hannover
Dr. Chris Oates	chris.oates@nist.gov	NIST	National Institute of Standards, Boulder, USA
Dr. Nathan R. Newbury	nathan.newbury@nist.gov	NIST	National Institute of Standards, Boulder, USA
Prof. Patrick Gill	patrick.gill@npl.co.uk	NPL	National Physical Laboratory, Teddington, UK
Dr. Rodolphe Le Targat	Rodolphe.Letargat@obspm.fr	SYRTE	Paris
Dr. Uwe Sterr	Uwe.Sterr@ptb.de	PTB	Physikalisch-Technische Bundesanstalt Braunschweig
Dr. Christian Lisdat	Christian.Lisdat@ptb.de	PTB	Physikalisch-Technische Bundesanstalt Braunschweig

Prof. Stephan Schiller	step.schiller@hhu.de **(Coordinator)**	UDUS	Heinrich-Heine-Universität Düsseldorf
Prof. Guglielmo M. Tino	guglielmo.tino@fi.infn.it	UniFi	Università di Firenze
Dr. Stephane Schilt	stephane.schilt@unine.ch	UniNe	Université de Neuchâtel
Prof. Kai Bongs	k.bongs@bham.ac.uk	UoB	University of Birmingham
Prof. Claus Lämmerzahl	claus.laemmerzahl@zarm.uni-bremen.de	ZARM	Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation, Bremen

Based on the results obtained in the SOC project (summarized in the publications Kai Bongs, et al. C. R. Physique 16, 553–564 (2015); http://dx.doi.org/10.1016/j.crhy.2015.03.009 and S. Origlia, et al., Proc. SPIE 9900, Quantum Optics, 990003; doi: 10.1117/12.2229473; http://arxiv.org/abs/1603.06062), ESA has decided to perform three technology development projects for a Sr lattice clock in space:

- Development of a laser at 461 nm and a laser at 689 nm
- Development of a clock control unit (actually: a device like the FSS)
- Development of a lattice laser at 813 nm

Some members of the SOC consortium most closely associated with the use of these devices consulted ESA on the specifications of the devices to be developed.

These projects are organized by the TEC department of ESA. The projects have started in 2016.

These developments are aimed to raise the TRL of the lasers currently used in the SOC project.

Some members will be involved in supporting these technology developments by providing test facilities of the contractors of the developments.

ESA has given the SOC team the task to develop the detailed experiment scientific document, that will be the foundation of a following phase-A study, including supporting funding.

ESA is about to launch a Phase-A project on the mission SOC in 2016. It will include a predesign of the space clock instrument.

4.2 Use and dissemination of foreground

Section A (public)

Peer-reviewed Publications:

B. Argence, E. Prevost, T. Lévèque, R. L. Goff, S. Bize, P. Lemonde, and G. Santarelli,
”**Prototype of an ultra-stable optical cavity for space applications”**,
Opt. Express 20, 25409-25420 (2012)

D. Sutyrin,, N.Poli,, N.Beverini,, S.V.Chepurov,, M.Prevedelli,, M.Schioppo,, F. a,, M. Tarallo, and G.M.Tino
“Frequency noise performances of a Ti: sapphire optical frequency comb stabilized to an optical reference”,
Optics Communications, 291-298 (2013)

N. Poli, C. W. Oates, P. Gill and G.M. Tino,
“**Optical atomic Clocks**”,
La Rivista del Nuovo Cimento, vol. 36, n. 12, p. 555 (2013).

F. Levi, D. Calonico,, A. Mura,, M. Frittelli,, C. Calosso,, M. Zucco,, C. Clivati,, G. A. Costanzo,, R. Ambrosini,, G. Galzerano,, P. D. Natale,, D. Mazzotti,, N. Poli,, D. V. Sutyrin, and G. M. Tino,
“**LIFT-the Italian Link for Time and Frequency**”
European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), 2013 Joint, pp. 477-80 (2013). Doi: 10.1109/EFTF-IFC.2013.6702195

Nevsky, A; Alighanbari, S; Chen, Q -F; Ernsting, I; Vasilyev, S; Schiller, S; Barwood, G; Gill, P; Poli, N; Tino, G M,
“**Robust frequency stabilization of multiple spectroscopy lasers with large and tunable offset frequencies**”,
Opt. Lett. 38, 4903-4906 (2013)

M. Schioppo,, N. Poli,, M. Prevedelli,, S. Falke,, C. Lisdat,, U. Sterr, and G. M. Tino,
“A compact and efficient strontium oven for laser-cooling experiments”,
Review of Scientific Instruments **83**, 103101-1/103101-6 (2012)

N. Poli, M. Schioppo, S. Vogt, S. Falke, U. Sterr, C. Lisdat, G. M. Tino,
“A transportable strontium optical lattice clock”,
Applied Physics B: 117 (2014), 4, 1107 – 1116; dx.doi.org/10.1007/s00340-014-5932-9

S. Häfner, S. Falke, C. Grebing, S. Vogt, T. Legero, M. Merimaa, C. Lisdat, U. Sterr,
“8×10^{-17} fractional laser frequency instability with a long room-temperature cavity”,
Optics Letters 40, 2112 – 2115 (2015); dx.doi.org/10.1364/OL.40.002112

S. Falke, Lemke, Nathan; Grebing, Christian; Lipphardt, Burghard; Weyers, Stefan; Gerginov, Vladislav; Huntemann, Nils; Hagemann, Christian; Al-Masoudi, Ali; Häfner, Sebastian; Sterr, Uwe; Lisdat, Christian;
“A strontium lattice clock with 3×10^{-17} inaccuracy and its frequency”,
New Journal of Physics: 16 (2014), [Online only]; dx.doi.org/10.1088/1367-2630/16/7/073023

Hagemann, Christian; Grebing, Christian; Lisdat, Christian; Falke, Stephan; Legero, Thomas; Sterr, Uwe; Riehle, Fritz; Martin, Michael J.; Ye, Jun,
„Ultrastable laser with average fractional frequency drift rate below 5 × 10^{-19}/s.",
Optics Letters: 39, 5102 – 5105 (2014); dx.doi.org/10.1364/OL.39.005102

Kai Bongs, Yeshpal Singh, Lyndsie Smith, Wei He, Ole Kock, Dariusz´ Swierad, Joshua Hughes,
Stephan Schiller, Soroosh Alighanbari, Stefano Origlia, Stefan Vogt, Uwe Sterr, Christian Lisdat, Rodolphe LeTargat, Jérôme Lodewyck, David Holleville,
Bertrand Venon, Sébastien Bize, Geoffrey P. Barwood, Patrick Gill, Ian R. Hill, Yuri B. Ovchinnikov, Nicola Poli, Guglielmo M. Tino, Jürgen Stuhler,
Wilhelm Kaenders for the SOC2 team,
"Development of a strontium optical lattice clock for the SOC mission on the ISS",
C. R. Physique 16, 553–564 (2015); http://dx.doi.org/10.1016/j.crhy.2015.03.009

D. Swierad et al,
"Next-generation ultra-stable clock laser system for space applications"
In preparation

Conference proceedings paper:

S. Origlia, S. Schiller, M.S. Pramod, L. Smith, Y. Singh, W. He, S. Viswam, D. Świerad, J. Hughes, K. Bongs, U. Sterr, Ch. Lisdat, S. Vogt, S. Bize, J. Lodewyck, R. Le Targat, D. Holleville, B. Venon, P. Gill, G. Barwood, I. R. Hill, Y. Ovchinnikov, A. Kulosa, W. Ertmer, E.-M. Rasel, J. Stuhler, W. Kaenders,, "Development of a strontium optical lattice clock for the SOC mission on the ISS", Proc. SPIE 9900, Quantum Optics, 990003 (April 29, 2016); doi: 10.1117/12.2229473; http://arxiv.org/abs/1603.06062

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[2]	Main leader	Title	Date/Period	Place	Type of audience[3]	Size of audience	Countries addressed
1	Exhibition	Schiller	Horizon 2020 und NRW	September 2013	Düsseldorf	Scientific Community; Industry	500	Germany
2	Presentation	Schiller	Highlights der Physik	29. September 2014	Saarbrücken	Civil society	150	Germany
3	Exhibition	Schiller	Highlights der Physik	September 2014	Saarbrücken	Civil society	300	Germany
4	Presentation	Bongs	British Science Festival	8. September 2014	Birmingham	Civil Society		England
5	Presentation	Schiller	Nacht der Wissenschaften	24. September 2015	Düsseldorf	Civil society	80	Germany
6	Presentation	Singh	Conference on European Life and Physical Sciences in space	Nov. 24, 2015	London	Civil society		England

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[2] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[3] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

7	Presentation	Smith		May 2013	Wolverhampton Girl’s High School	Civil society		England
8	Exhibit	Sterr	PTB Open day	August 2016	Braunschweig	Civil society		Germany
9	Exhibition	Schiller	Highlights der Physik	September 2016	Ulm	Civil society	300	Germany

I. Presentations have been given at the following conferences:

- 2011 ESA Optical clocks workshop, Trani (PTB, talk)
- 2012 EU – SPACE conference, Cyprus. Nov. 2012 (UoB talk and poster)
- 2012 EFTF (UDUS, on FSS and Yb clock)
- 2012 EGAS (UNIFI talk on Sr clock)
- 2012 ICAP (UNIFI poster on Sr clock)
- 2012 Workshop on Group 2 atoms (Tokio, UNIFI talk on Sr clock)
- 2012 Metrology of time and Space, Moscow (UNIFI, talk on Sr clock)
- 2013 Quantum to Cosmos (Nizza): (UoB contribution)
- 2013 Spring Meeting of the German Physical Society: poster on UDUS Yb clock
- 2013 Europ. Time and Frequency Forum (Prague): poster on FSS, poster on UDUS Yb clock, poster on UNIFI 1st generation Sr clock
- 2013 Conf. on Lasers and Electrooptics (Munich); talk on SOC, talk on frequency combs
- 2013 Intl. Conf. on Laser Spectroscopy (Berkeley, USA); poster on SOC
- 2013 CPT13 (Bloomington, USA); poster on SOC
- 2013 QUAMP: Swansea, Wales, September 2013, poster “Sr lattice clock for space” by Lyndsie Smith et al.
- S. Schiller, “Perspectives for precision experiments in space with cold-atom clocks”, lecture at the International Conference „Fundamentals and Applications of Ultra-Cold Matter“, 16. – 19. Sept. 2013, Visselhövede, Germany
- 2014 Spring Meeting of the German Physical Society; presentation by S. VOGT et al. on Sr clock, and G. Mura on Yb clock
- 2014 EFTF Neuchatel, Switzerland (contribution by UoB, PTB)
- 2014, Nottingham Conference, Relativistic Quantum Metrology (7-8 March, 2014): Talk by UoB.
- S. Schiller “Optical Frequency Metrology and future Space Missions”, Colloquium VNIFTRII, Mendelejevo, March 21, 2014
- S. Schiller, “Optical Frequency Metrology and future Space Missions”, Colloquium Lebedev Institute, Moscow, March 24, 2014
- C. Lisdat, “Lattice clocks at PTB: current status and applications”, Colloquium of the State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, 09, May, 2014, China

- C. Lisdat, “Lattice clocks at PTB: current status and applications”, Colloquium of the Time and Frequency Department of NIM, Beijing, 06, May, 2014, China
- L. Smith, “Clocks and ultra precision”, oral presentation at the University of Oslo, May 2014.
- K. Bongs, “From clocks to gravity mapping”, oral presentation at the NPL-DSTL quantum showcase meeting, May 15, 2014, NPL Teddington
- L. Smith et al., “Transportable Sr optical lattice clock”, poster, International Navigation Conference, Manchester, February 2015.
- L. Smith, “Sr lattice clock for space”, oral presentation at the DPG, Heidelberg, Germany, March 2015.
- S. Vogt, et al. “Characterization of a transportable Strontium lattice clock”, DPG-Frühjahrstagung, Berlin, 17-21, März, 2014, Deutschland
- C. Lisdat, “Optical clocks: Recent developments and outlook” [invited lecture], Rcontres de Moriond and GRAM Colloquium on Gravitation: 100 years after GR, La Thuile, Aosta Valley, 21-28, March, 2015, Italy
- L. Smith, …, S. Dörscher [speaker], “Development of a strontium optical lattice clock for space applications” [poster], 2015 Joint IEEE International Frequency Control Symposium and 29th European Frequency and Time Forum, Denver, 12-16, April, 2015, USA
- J. Grotti, et al. „Characterization of a transportable Sr lattice clock” [poster], The 21st Young Atom Opticians Conference, Zürich, 19-24, April, 2015, Switzerland
- C. Lisdat, “Transportable optical clocks – an overview”, presentation to the Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT) of the Consultative Committee for Time and Frequency (CCTF), 15.09.2015, Bureau International des Poids et Mesures (BIPM), Sèvres, Frankreich
- S. Schiller et al. “The Space Optical Clocks Project”, poster at 591. WE-Heraeus-Seminar on Astrophysics, Clocks and Fundamental Constants, 27 - 30 May 2015 at the Physikzentrum Bad Honnef, Germany
- Y. Singh et al. “Development of a strontium optical lattice clock for space applications”, poster, CLEO Munich, June 2015
- S. Schiller, “Fundamental Tests and Space: Optical Frequency Metrology and Future Space Missions”, invited lecture at the 1st School on Optical Clocks, INRIM, Torino (Italy), 29.6. – 3.7. 2015
- Sruthi et al, “Space optical clock”, poster, 1st School on Optical Clocks, INRIM, Torino (Italy), 29.6. – 3.7. 2015
- Y. Singh, “Transportable/Portable/Space Optical Lattice Clock”, oral presentation at the Quantum Sensing and Atom-Surface Interactions conference in Natal, Brazil on Aug 17, 2015.
- S. Schiller, “Optical Clocks in Space”, Sino-German Symposium on Gravitational Physics in Space, invited talk, Hannover, 13. - 17. September 2015
- “Space optical clock”, poster, Measurement and Metrology Workshop of the ITN “FACT”, Observatoire de Paris, September 2015.
- Y. Singh et al. “Development of a strontium optical lattice clock for the SOC Space Optical Clocks mission on the ISS”, poster, 8th Symposium on Frequency Standards and Metrology, Potsdam, Germany, October 2015.

- G. Mura et al. “The SOC2 Yb optical lattice clock”, poster, 8th Symposium on Frequency Standards and Metrology, Potsdam, Germany, October 2015.
- S. Schiller, “The ISS Space Optical Clock Mission", ISSI/HISPAC Workshop on “High Performance Clocks in Space Science”, invited talk, Bern, 30 November - 4 December 2015
- S. Schiller, “The Space Optical Clocks mission on the ISS”, Colloquium of the Graduiertenkolleg 1729 “Ultracold Matter and Applications”, Hannover, 7. January 2016
- S. Schiller, “The Space Optical Clock Mission on the ISS”, Research Community Consultation Workshop on Life and Physical Sciences in Space, 18-20 January 2016, ESTEC, Noordwijk, Netherlands
- S. Origlia et al., “Development of a strontium optical lattice clock for the SOC mission on the ISS”, talk, SPIE Photonics Europe 2016, 3.-7. April 2016, Bruxelles, Belgium
- S. Schiller, “The Space Optical Clocks mission on the ISS: concept and development of a prototype lattice clock”, invited talk, 609. WE-Heraeus-Seminar on Relativistic Geodesy: Foundations and Applications, March 13-19, 2016, Physikzentrum Bad Honnef, Germany
- B. Eder, A. Kulosa, S. Schilt, L. Balet, S. Lecomte, M. Hutterer, L. Pedrosa Rodriguez, D. Parker, Y. Singh, K. Bongs, E. Rasel, “Robustness testing of a compact auxiliary laser for an optical atomic clock under space conditions”, Submitted to EFTF 2016, 30th European Frequency and Time Forum, York, UK; April 4-7, 2016
- Y. Singh et al. “Development of a breadboard optical atomic clock for the SOC mission on the ISS”, submitted to 41st Committee of Space Research (COSPAR) Scientific Assembly will be held from 30 July - 7 August 2016, in Istanbul, Turkey.

Section B (public)

Part B1

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[4]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
Patent	NO		GB1409734.9, PCT/GB2015/050876	Controlled Atom Source	University of Birmingham

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[4] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Type of Exploitable Foreground[5]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[6]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	OPTICAL CLOCKS FOR SPACE	NO		KNOW-HOW FOR PRODUCING A SPACE INSTRUMENT	PHYSICS AND GEODESY RESEARCH	2016		
Commercial exploitation of R&D results	ATOM OVEN AND ATOM CHAMBERS	NO		COMPONENTS	PHYSICS RESEARCH	2016		
Commercial exploitation of R&D results	LASERS FOR OPTICAL CLOCKS	NO		LASERS	PHYSICS RESEARCH	2015		
Commercial exploitation of R&D results	IMPROVED FREQUENCY COMBS	NO		FEMTOSECOND FREQUENCY COMB	PHYSICS AND METROLOGY RESEARCH	2015		

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[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[6] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

1. Specific webpage promoting collaborations stemming from the project

This webpage (red text on the left menu of www.soc2.eu) is intended to give an overview of the topics on which the teams can offer collaborations, small and large, ranging from consulting to joint measurements and technology transfer. A number of topics on which the consortium partners can offer collaborations is displayed.

The webpage is a wiki, which each SOC partner can modify or extend, after entering a password. The wiki is rather straightforward to use. There is an online help.

2. Spin-off companies

Partner UniFi has founded a company, AtomSensors (Italy), which offers subsystems for optical clocks. They are based in part on the development UniFi could perform under ESA and EU-FP7 funding during the SOC project.

3. Additional funding procurement

The SOC consortium was engaged in continuing the developments beyond this concrete project and has been active in proposing follow-on activities and successful in winning grants:

A. Partner UBHAM is coordinating an EU Initial Training Network, called FACT (future atomic clock technology), which has started in October 2013. Here, 13 Ph.D. students are working on various aspects of optical clocks, in particular improvement of accuracy, transportable clocks, and new technological solutions.

B. Within the studies on the ESA satellite mission STE-QUEST, funding has been awarded by national space agencies to NPL, PTB and UDUS for the development of ultrastable cavities for space and microwave generation from lasers locked to such cavities. In addition radiation resistance of high-finesse mirrors and influence on ULE spacers has been investigated and results obtained. In part this has already been published (Q. Chen, A. Yu. Nevsky, S. Schiller, E. Portuondo Campa, S. Lecomte, D. Parker, “Radiation resistance of dielectric mirrors for high-finesse optical resonators”, Appl. Phys. B 116, 385–391 (2014); DOI 10.1007/s00340-013-5704-y). This has relevance for SOC as well.

C. Partner UBHAM is coordinating a Horizon 2020 – RISE project called “Q-Sense: Quantum sensors - from the lab to the field”, which deals, in part, with the further development of compact and transportable optical clocks. Several teams of SOC are also members of Q-Sense. The project started on Jan. 1, 2016 and will last for 4 years.

D. Partner UDUS has obtained a Marie Sklodowska Curie Action Individual Fellowship in Horizon 2020 for a post-doctoral fellow that will work on the further development of the SOC2 Sr clock. The fellowship will start in mid-2016 and last 2 years.

E. Partner UNIF and KI have obtained a development project “SOARA” from the Italian Space Agency ASI with the goal of developing an advanced atomics chamber for space.

4. Commercial activities

Partners TOPTICA and MENLO are now offering products (lasers, frequency combs) aimed at use with lattice clocks. Their participating in the SOC consortium has supported their internal development and commercialization efforts.

4.3 Report on societal implications

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	263500
Title of Project:	SOC2—Towards Neutral-atom Space Optical Clocks:
Name and Title of Coordinator:	Prof. Stephan Schiller

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***0Yes XNo***
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO
• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO
• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	NO
• Were those animals transgenic farm animals?	NO
• Were those animals cloned farm animals?	NO
• Were those animals non-human primates?	NO
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	NO
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	NO
DUAL USE	
• Research having direct military use	0 Yes X No
• Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		1
Work package leaders		6
Experienced researchers (i.e. PhD holders)	1	12
PhD Students	1	3
Other		

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men: 4	5

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ X	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				**Very effective**
☐	Design and implement an equal opportunity policy	○	○	○	○	○
☐	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
☐	Organise conferences and workshops on gender	○	○	○	○	○
☐	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

X No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

X Yes- please specify: listed under Table A2

○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

X No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

○ Main discipline[7]: 1.2

○ Associated discipline[7]:

○ Associated discipline[7]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ X	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

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[7] Insert number from list below (Frascati Manual).

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No
X Yes- in framing the research agenda
○ Yes - in implementing the research agenda
○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

13b If Yes, in which fields?

Agriculture
Audiovisual and Media
Budget
Competition
Consumers
Culture
Customs
Development Economic and Monetary Affairs
Education, Training, Youth
Employment and Social Affairs

Energy
Enlargement
Enterprise
Environment
External Relations
External Trade
Fisheries and Maritime Affairs
Food Safety
Foreign and Security Policy
Fraud
Humanitarian aid

Human rights
Information Society
Institutional affairs
Internal Market
Justice, freedom and security
Public Health
Regional Policy
Research and Innovation
Space
Taxation
Transport

13c If Yes, at which level?

○ Local / regional levels
○ National level
○ European level
○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**11**
To how many of these is open access[8] provided?	
How many of these are published in open access journals?	**1**
How many of these are published in open repositories?	**6**
To how many of these is open access not provided?	**4**
Please check all applicable reasons for not providing open access:	
☐ publisher's licensing agreement would not permit publishing in a repository ☐ no suitable repository available X no suitable open access journal available ☐ no funds available to publish in an open access journal X lack of time and resources ☐ lack of information on open access ☐ other[9]: ……………	
15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**1**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	
	Registered design	
	Other	

17. How many spin-off companies were created / are planned as a direct result of the project?	**1**
Indicate the approximate number of additional jobs in these companies:	**2**

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

X	Increase in employment, or	X	In small & medium-sized enterprises
☐	Safeguard employment, or	☐	In large companies
☐	Decrease in employment,	☐	None of the above / not relevant to the project
☐	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:* 2

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[8] Open Access is defined as free of charge access for anyone via Internet.

[9] For instance: classification for security project.

Difficult to estimate / not possible to quantify	☐

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes X No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes X No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

☐	Press Release	☐	Coverage in specialist press
☐	Media briefing	☐	Coverage in general (non-specialist) press
☐	TV coverage / report	☐	Coverage in national press
☐	Radio coverage / report	☐	Coverage in international press
☐	Brochures /posters / flyers	X	Website for the general public / internet
☐	DVD /Film /Multimedia	X	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

X	Language of the coordinator	X	English
☐	Other language(s)		

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES
1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as

geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES
3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

2. FINAL REPORT ON THE DISTRIBUTION OF THE EUROPEAN UNION FINANCIAL CONTRIBUTION

This report shall be submitted to the Commission within 30 days after receipt of the final payment of the European Union financial contribution.

Report on the distribution of the European Union financial contribution between beneficiaries

Name of beneficiary	Final amount of EU contribution per beneficiary in Euros
1.	
2.	
n	
Total	