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Report on Activities to the 18th Session of the Consultative Committee for Time and Frequency, June 2009

This report covers the activities pursued in PTB concerning

1. primary clocks
2. atomic-time scales
3. time and frequency comparisons
4. optical frequency standards/clocks
5. optical frequency measurements.

1. Primary clocks

1.1 Fountain clock CSF1

CSF1 is a caesium fountain clock using the (100)-geometry of the laser beams for the capture of caesium atoms in a magneto-optical trap. After a molasses phase the atoms traverse a state-selection cavity before reaching the main microwave cavity and continuing the ballistic flight. Since CSF1 became operational, it was run 21 times under routine operating conditions for periods of 15-25 days each. The results were submitted to BIPM and served for the measurement of the TAI scale unit [1]. At the time the CSF1 u_B was estimated as $\leq 1\times10^{-15}$ [2].

Recently, significant progress was made with respect to the CSF1 frequency instability and to the reliability as well. Improvements of the setup for the detection of the atoms, the master-laser frequency stabilization, and the timing of the fountain cycle resulted in significant improvements of the signal-to-noise ratio. During recent measurements of the TAI scale unit, the interruption of the CSF1 operations amounted to much less than 0.1% of the total measurement interval, so that $u_{l/lab}$ was evaluated to be far below $0.1\times\cdot10^{-15}$.

For the two TAI scale unit measurements in 2008 and the most recent one in 2009 the newly developed microwave frequency synthesis [3] was used. It had been demonstrated before that this new synthesis setup is capable of providing instabilities below the 10^{-16} level. During a recent measurement of the single ytterbium ion clock transition frequency the Allan standard deviation was dominated by the white frequency noise of CSF1 for all averaging times and not limited any more by instabilities of the hydrogen maser. Under this conditions a $\tau^{-1/2}$-dependence down to 4×10^{-16} at 10^5 s averaging time could be demonstrated for the first time. Therefore - in contrast to previous TAI scale measurements - the statistical uncertainty of CSF1 has been and will be in the future calculated with the assumption of white frequency noise for the total measurement interval. A statistical uncertainty $u_A(\tau = 25\ \mathrm{d}) = 0.1\times10^{-15}$ can thus be assumed.

To go even a step further, the low frequency instability of PTB's Yb^+-ion optical clock reference laser at 344 THz was transferred to a 9.6 GHz-microwave oscillator using a fibre-based femtosecond laser frequency comb as a transfer oscillator [4]. It was demonstrated that there are no significant noise contributions from this optically stabilized microwave signal when used as source for the excitation of the caesium atoms in the usual operation mode of CSF1. Moreover, the optically stabilized microwave source was locked to CSF1 and frequency measurements against a hydrogen maser were performed. A significant decrease of the CSF1 frequency instability to $7.4\times10^{-14}\,(\tau/\mathrm{s})^{-1/2}$ was observed [5]. To our knowledge this is the first time that an optically generated microwave has been used in a caesium frequency standard.

1.2 Fountain clock CSF2

A first evaluation of the uncertainty of the second atomic fountain CSF2 [6,7] at PTB has recently been performed. The fountain uses the (1,1,1) optical molasses geometry for laser cooling, which allows the use of large-diameter laser beams. The use of large laser beam diameters and optimized phase gradient cooling results in a caesium cloud with 6 mm ($1/e^2$ level) radius and a temperature below 1µK. The fountain operates with a cycle which optimizes the contributions from the quantum projection noise and the Dick effect, resulting in a short-term frequency instability $\sigma_y=2.5\times10^{-13}(\tau/s)^{-1/2}$. First comparisons with the first fountain primary frequency standard at PTB showed agreement within the uncertainties of the standards, and demonstrated a long-term fractional instability below 0.7×10^{-15} for a measurement period of 15 days. The total type B uncertainty of the standard is still being investigated, but is expected to be on the order of 1×10^{-15} or below. So far the largest contributions to the uncertainty budget come from the collisional shift, the distributed cavity phase shift and the observed microwave power dependence of the fountain frequency. Due to the lower cloud density and temperature in comparison with the first fountain CSF1 at PTB, a reduced shift due to cold collisions is observed. Also the observed microwave power dependence is smaller. It is expected that with the implementation of a slow beam for atom loading, and an improved frequency synthesis, the short-term instability of the fountain will be reduced further, and effects related to the atom density will be determined with better accuracy.

1.3 Thermal beam clocks

PTB CS1 and CS2 [8] have continued to function over the years. The clocks' operational parameters were checked periodically and validated to estimate the clock uncertainty. These parameters are the Zeeman frequency, the temperature of the beam tube (vacuum enclosure), the line width of the clock transition as a measure of the mean atomic velocity, the microwave power level, the spectral purity of the microwave excitation signal, and some characteristic signals of the electronics. Up to now, the findings did not call for a modification of the previously stated relative frequency uncertainties, u_B, which are 8×10^{-15} and 12×10^{-15} for CS1 and CS2, respectively [9]. The clocks have been operated continuously, and time differences *UTC(PTB) − clock* in the standard ALGOS format were reported to BIPM so that $u_{l/lab}$ is zero. Only in 2008 PTB CS1 and CS2 could not be operated as undisturbed as used to from the past. A brief explanation of the defects and consequences for each clock is given subsequently.

CS1

During 2008, the CS1 beam signal gradually decreased and in consequence the frequency instability increased. Opening the vacuum chamber, cleaning the oven nozzle and the magnet bore in front of the oven, and improving the quality of vacuum gaskets lasted much longer than anticipated, and thus CS1 could not serve as a primary clock during the months of November and December 2008. The repair, fortunately, was very successful: The beam signal now is at a much higher level than at any time during 2008. The value $u_A(\tau = 30d, CS1) = 5\times10^{-15}$ stated in CircularT is now an even more conservative estimate. Reversals of the beam direction have been performed three times per year on average, and the beam reversal frequency shift has exhibited the normal scatter around the long term mean value.

CS2

CS2 has been operated with two 5 gram charges of caesium in the two ovens since the mid eighties. So it was no real surprise that one oven ran empty in summer 2008. The signal drop was slow enough and lasted a couple of hours so that the quartz remained locked all time. Since then the second beam has been in operation. When it runs empty as well, a major refurbishment will be undertaken. Except of the few hours in summer with a very low beam signal, the uncertainty contribution $u_A(\tau = 30d, CS2) = 3\times10^{-15}$ has been valid.

Obviously, no beam reversal can be performed for the time being. This has an impact on the statement of u_B related to the contribution of the end-to-end cavity phase difference. The respective u_B uncertainty contribution amounts to 10×10^{-15} and dominates the CS2 total uncertainty budget [9]. In Figure 1, the results of all determinations of the beam-reversal frequency F_{BR} shift since May 1997 are shown. Day zero represents the date of the last successful beam reversal, MJD 54628 = 2008-06-11. The standard deviation of the individual values around the regression is explained by the CS2 frequency instability. To the right the predicted variation of F_{BR} is shown, assuming that the linear trend would continue. The various lines indicate the statistical uncertainty of this prediction based on the fit on the past data. The dashed lines indicate the currently estimated u_B uncertainty contribution. At day 1000 this estimate will have to be enlarged by 1×10^{-15} because of the prediction uncertainty.

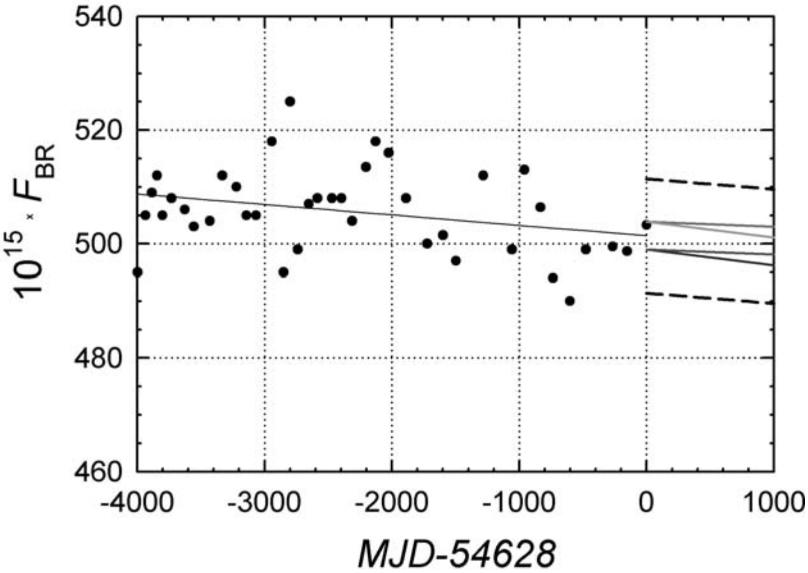

Figure 1: CS2 frequency difference F_{BR} recorded after beam reversal at the indicated dates. Each point is based on 10-day averages of the CS2 frequency with respect to the available frequency standards in PTB. Prediction of F_{BR} and the associated uncertainties are explained in the text.

2. Time Scales

PTB continues to realize UTC(PTB) from the 5 MHz output of CS2 and an associated phase micro stepper whose rate is adjusted in steps of 0.5 ns/d at the end of a month if required to keep the time scale in reasonable agreement with UTC. The steering values are published in PTB's Time Service Bulletin.

A system for the realization of UTC(PTB) based on the output frequency of a hydrogen maser steered towards the frequency of CSF1, or towards other sources, such as CS1, alternatively, has been established. The system will remain in a back-up mode as long as the CS2 remains in function. This will allow detailed tests of optimum frequency prediction and steering to be made.

3. Time and Frequency Comparisons

GPS evaluation techniques, MC AV, P3 AV and PPP, and Two–Way Satellite Time and Frequency Transfer (TWSTFT) have been employed or studied by BIPM in the context of the realization of TAI. PTB provides GPS data of one single frequency and one dual frequency multi-channel receiver, and of its IGS-registered receiver, a geodetic time-oriented receiver. PTB provides as backup data from three further receivers which could in principle allow seamless availability of all kinds of required data.

PTB undertakes TWSTFT in the bi-hourly comparisons using Ku-band transponder capacity on a communication satellite with European and U.S. institutes, namely AOS, INRiM, IPQ, LNE-SYRTE, METAS, NIST, NPL, OCA, ROA, SP, TUG, USNO, and VSL.

The completely independent TWSTFT link between USNO and PTB, with transponder frequencies in the X-band, has also been continuously operated. Initially, part of the station operated at PTB was on loan from USNO, meanwhile PTB invested in new components to improve the reliability of the link. Time transfer data *UTC(USNO)-UTC(PTB)* are provided on a daily basis on the PTB ftp server.

The TWSTFT network connecting European and Asian stations has made good progress. Initially relying on the multi-channel time-transfer modems developed by NICT, now alternately a SATRE modem is used. In spring 2009, KRISS, NICT, NMIJ, NTSC, and TL participate on the Asian side, and OP, VSL and PTB on the European side. NIM is about to join the network. The causes of diurnal variations appearing in the measurements have been studied, but without fully conclusive results [10]. An agreement to share the cost for the transponder lease from mid 2009 onwards has been made. These costs have up to now been carried generously by NICT alone.

Unfortunately it must be stated that the operation of the TWSTFT links is not contractually stable and guaranteed for a long time. After replacement of aged satellites the providers cannot always offer similar transponder capacity on new satellites at the same contractual conditions. Further development of TWSTFT in terms of higher precision and possibly higher accuracy has been hindered by such difficulties, last not least by the unacceptable high cost.

Calibration activities with PTB involvement during 2006 - 2008:
1) GPS - TAIP3:
Three Calibrations of the geodetic type receiver in the framework of a BIPM campaign were performed in July 2006, February 2007, and April 2008, respectively.

2) TWSTFT:
Three calibration exercises of Ku-band links were performed, involving the following institutes:

No.	Year	Participating Institutes	Reference
1	2006	TUG-PTB-METAS-TUG	[11]
2	2007	TUG-BEV-PTB-TUG	[12]
3	2008	TUG-PTB-NPL-OP-INRiM-VSL-METAS-TUG	to be published

Calibration constants with estimated uncertainties down to 0.9 ns were achieved in these campaigns. The reproducibility of TWSTFT calibrations could be tested on some of the links during campaign No. 3. The mean deviation between the actual and previously determined calibration values for links to PTB was < 0.5 ns. This confirms the feasibility of time scale comparisons with 1-ns-uncertainty as reported in a detailed analysis of European and transatlantic campaigns involving PTB [13]. In campaign No. 2 the GPS time link between BEV and PTB was calibrated by means of TWSTFT. The type-B uncertainty of this link could be reduced by nearly a factor of 2.
Calibrations of the X-band link were carried out by USNO in January 2006 and March 2007, and changes to the calibration constants were as well at the nanosecond level only. The next calibration is scheduled to happen in May 2009.

4. Optical frequency standards/clocks
PTB operates several optical frequency standards based on single ions and on neutral atoms:

4.1 688 THz Yb^+ single-ion frequency standard
This optical frequency standard uses the $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ electric-quadrupole transition of $^{171}Yb^+$ which has a natural linewidth of 3.1 Hz. Based on previous absolute frequency measurements and comparisons between two traps at PTB [14, 15], the unperturbed frequency of this transition has been recommended as a secondary representation of the second [16].

The software control of the experimental setup of the $^{171}Yb^+$ standard and of the measurement sequence has been optimized and extended. Important operation parameters can now be monitored remotely and unattended continuous operation intervals of 24 h are routinely achievable. Using a differential servo scheme, a number of systematic frequency shifts can now be evaluated without external reference and with a quantum projection noise limited statistical uncertainty in the range of $\sigma_y(10^4\ s) \approx 1\cdot10^{-16}$. Other improvements concerned the accuracy of the setting of the orientation of the static magnetic field during excitation of the reference transition. Now it is possible to switch between three field orientations that are mutually orthogonal to within 2°.

Taking advantage of these improvements, the tensorial shift of the reference transition frequency was repeatedly determined with an uncertainty of less than 0.1 Hz [17]. We expect that in our case the tensorial shift predominantly results from the quadrupole shift due to the electrostatic stray field gradient at trap centre whereas tensorial Stark shifts due to the trap field, anisotropic thermal radiation, and laser stray light play a minor role. In four measurements spanning a time interval of 70 days, the observed tensorial shift magnitudes varied in the range between 0.1 Hz and 0.5 Hz. The largest variation occurred upon loading a new ion.

In the time between Aug. 6 and Sept. 8, 2008, three absolute frequency measurements were carried out using CSF1 as the reference. The difference between the largest and the smallest measurement result was 0.23 Hz, corresponding to a relative spread of $3.3\cdot10^{-16}$. The statistical uncertainty of the frequency measurement data was in the range of $u_A = 5\cdot10^{-16}$ ....$8\cdot10^{-16}$ and was essentially determined by the instability characteristic of CSF1 and the employed averaging times of up to 90 h. As in previous absolute frequency measurements [18], the Yb^+ trap was operated at room temperature and the calculated blackbody shift of the Yb^+ transition frequency of -0.37(5) Hz at T = 300 K was not taken into account as a correction.

In the 2008 frequency measurements, the estimated systematic uncertainty of the reference was $u_B(CSF1) = 0.9\cdot10^{-15}$ and the systematic uncertainty of the Yb^+ standard was estimated as $u_B(Yb^+) = 0.5\cdot10^{-15}$. The dominant contributions to $u_B(Yb^+)$ are [19]: (i) an uncertainty of the applied tensorial shift correction of 0.2 Hz; (ii) a contribution of 0.2 Hz due to scalar light shifts potentially caused by spurious thermal radiation sources and laser stray light; (iii) a servo error contribution of 0.1 Hz; (iv) an uncertainty of 0.05 Hz of the applied quadratic Zeeman shift correction (magnitude 1.13 Hz). The uncertainty assumed for the tensorial shift correction is larger than that of the tensorial shift measurements because only one of these measurements was performed simultaneously with a frequency measurement. For the other two frequency measurements, the corrections were determined by linear interpolation between two tensorial shift measurements separated by 44 days. The increased uncertainty of the tensorial shift correction takes into account the lack of information on the actual temporal variation of the tensorial shift.
The weighted mean of the 2008 measurements of the $^{171}Yb^+\ ^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ transition frequency is $\nu(Yb^+)$ = 688 358 979 309 306.6 Hz. The difference to the previously determined frequency value is 1.1 Hz which is within the inferred systematic uncertainty of the previous measurements [20]. The combined uncertainty of the new frequency measurement is $(u_A^2 + u_B^2(CSF1) + u_B^2(Yb^+))^{1/2} = 0.8$ Hz.

4.2 Spectroscopy of the 642 THz electric-octupole transition of Yb^+

A laser system for high-resolution spectroscopy of the E3 (electric-octupole) transition of Yb^+ at 642 THz has been set up. Recently the frequency stability of this laser was tested by determining the combined instability of the probe laser of the 688 THz Yb^+ standard and of the 642 THz laser. It appears that the stabilities of both lasers are essentially limited by the thermal noise of their reference cavities which corresponds to laser linewidths in the range of a few Hertz. First absorption spectra of the E3 transition with approximately Fourier-limited linewiths in the range of 12 Hz to 30 Hz were recorded. The present observations with respect to the light shift of the transition are entirely consistent with measurements performed by the NPL group [19]. Our investigations are however still in a very early stage and thus have not yet provided quantitative data that could serve as a test of the recent absolute frequency measurement reported by the NPL group [19].

4.3 Neutral-atom frequency standards

The work on PTB's optical frequency standard based on the 657 nm $^1S_0 - {}^3P_1$ transition (f = 455.986 THz) in an ultracold ($T \approx 15$ µK) ballistically expanding atomic cloud of calcium atoms was stopped in favour of a strontium optical lattice clock. The ultrastable 1-Hz linewidth laser of the calcium standard still serves as reliable short-term reference for the comparison of optical clocks via fibre networks.

In the optical strontium clock up to 10^7 ^{88}Sr atoms at a temperature of 2 to 4 µK are trapped in a horizontal magic-wavelength optical lattice within a cooling time of a few hundred milliseconds. The 698 nm interrogation laser is locked to a vibration-insensitive cavity [20]. We have investigated the influence of collisions on the operation of the clock [21] and observed and quantified inelastic losses, line broadening and shifts. With these data operational parameters of a ^{88}Sr lattice clock at an uncertainty of $1\cdot10^{-16}$ could be defined. A minimum linewidth of the clock transition of 20 Hz was achieved.

Currently the system is extended to ^{87}Sr to perform a frequency measurement. A cryogenically cooled environment is being set up that will allow to perform measurements where the fractional blackbody shift is reduced well below 10^{-17}.

Apart from PTB's activities an Yb lattice clock is currently being set up at the university of Düsseldorf.

5. Optical frequency measurements

For optical frequency standards PTB operates fiber-based frequency comb generators for use in transportable and long-term stable optical clocks.

We tested the accuracy of fibre laser based frequency combs by performing direct frequency comb comparisons. In a first experiment in co-operation with the University of Konstanz and the Max Planck Institute for Quantum Optics München, a stable optical frequency near 1545 nm was simultaneously measured by two independent comb systems, giving an agreement to within 6×10^{-16} [22]. For long-term measurements of the Yb^+ ion transition we obtained an agreement to within a few parts in 10^{-17} [15].

We have phase-stabilised a fibre laser at 194 THz to an optical frequency standard at 344 THz using a fibre-based femtosecond frequency comb and thus transferred the properties of an optical frequency standard to another spectral region. Relative to the optical frequency standard, the synthesised frequency at 194 THz is determined to within 1 mHz and its fractional frequency instability is measured to be less than 2×10^{-15} at 1 s, reaching 5×10^{-18} after 8000 s. We also measured the synthesised frequency against a caesium fountain clock: here the frequency comparison itself contributes less than 4 mHz (2×10^{-17}) to the uncertainty. Our results confirm the suitability of fibre based frequency comb technology for precision measurements and frequency synthesis, and enable long-distance comparison of optical clocks by using optical fibres to transmit the frequency information [23].

In collaboration with LNE-SYRTE we used our transportable fs comb to measure the frequency of the ^{87}Sr lattice clock [24] and explored the potential of a long-haul frequency comparison using optical fibres [25].

In 2006 we performed a first frequency measurement on a thermal ^{24}Mg atomic beam [26].

Recently, we have established a fibre link to the university of Hanover and measured the frequency of the ^{24}Mg intercombination transition with respect to a primary clock at PTB [27].

References

[1] P. Wolf, G. Petit, E. Peik, C. Tamm, H. Schnatz, B. Lipphardt, S. Weyers, R. Wynands, J.-Y. Richard, S. Bize, F. Chapelet, F. Perreira dos Santos, A. Clairon, Proc. 20th European Frequency and Time Forum (EFTF), Braunschweig, March 2006, 476-485
[2] S. Weyers, A. Bauch, R. Schröder and Chr. Tamm, Proc. 6th Symposium on Frequency Standards and Metrology, St. Andrews, September 2001, 64-71
[3] A. Sen Gupta, R. Schröder, S. Weyers and R. Wynands, in: Proceedings of the 21st European Frequency and Time Forum (EFTF), Geneva, pp. 234-237 (May/June 2007)
[4] B. Lipphardt, G. Grosche, U. Sterr, Chr. Tamm, S. Weyers, H. Schnatz, IEEE Trans. Instr. Meas. **58**(4), 1258-1262 (2009)
[5] S. Weyers, B. Lipphardt, and H. Schnatz, Phys. Rev. A **79**, 031803(R) (2009)
[6] R. Wynands, D. Griebsch, R. Schröder, and S. Weyers, Proc. 20th European Frequency and Time Forum (EFTF), Braunschweig, March 2006, 200-202
[7] N. Nemitz, V. Gerginov, R. Schröder, S. Weyers, and R. Wynands, Proc. 7th Symposium on Frequency Standards and Metrology, Asilomar. October 2008, to be published
[8] A. Bauch, Metrologia **42**, S43-S54 (2005)
[9] T. Heindorff, A. Bauch, P. Hetzel, G. Petit, S. Weyers, Metrologia **38**, 497-502 (2001)

[10] D. Piester, A. Bauch, M. Fujieda, T. Gotoh, M. Aida, H. Maeno, M. Hosokawa, S. H. Yang, Proc. 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 Nov 2007, Long Beach, California, USA, pp. 211-222 (2008)
[11] C. Schlunegger, G. Dudle, L.-G. Bernier, D. Piester, J. Becker, B. Blanzano, Proc. IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum, Geneva, Switzerland, 29 May – 1 Jun 2007, pp. 918-922 (2007)
[12] A. Niessner, W. Mache, B. Blanzano, O. Koudelka, J. Becker, D. Piester, Z. Jiang, F. Arias, (submitted to 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-4 Dec 2008, Reston, Virginia, USA)
[13] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, O. Koudelka, Metrologia **45**, 85-198 (2008)
[14] T. Schneider, E. Peik, Chr. Tamm, Phys. Rev. Lett. **94**, 230801 (2005).
[15] Chr. Tamm, B. Lipphardt, H. Schnatz, R. Wynands, S. Weyers, T. Schneider, E. Peik, IEEE Trans. **IM-56**, 601 (2007)
[16] http://www.bipm.org/utils/common/pdf/CCTF17.pdf
[17] Chr. Tamm, S. Weyers, B. Lipphardt, E. Peik, Manuscript in preparation
[18] http://www.bipm.org/wg/CCL/CCL-CCTF/Allowed/2005/PTB_Yb.doc
[19] K. Hosaka, S.A. Webster, A. Stannard, B.R. Walton, H.S. Margolis, P. Gill, Phys. Rev. A **79**, 033403 (2009)
[20] T. Legero, C. Lisdat, J. S. R. Vellore Winfred, H. Schnatz, G. Grosche, F. Riehle and U. Sterr, IEEE Trans. Instrum. Meas. **58**, 1252-1257 (2009)
[21] C. Lisdat, J. V. Winfred, T. Middelmann, F. Riehle and U. Sterr, arXiv:0904.2515v1 [physics.atom-ph] (2009)
[22] P. Kubina, P. Adel, F. Adler, G. Grosche, T.W. Hänsch, R. Holzwarth, A. Leitenstorfer, B. Lipphardt, H. Schnatz, Opt. Express **13** (3), 904-909 (2005)
[23] G. Grosche, B. Lipphardt, H. Schnatz, Eur. Phys. J. D 48, 27-33 (2008) ; DOI: 10.1140/epjd/e2008-00065-7
[24] X. Baillard, M. Fouché , R. Le Targat, P. Westergaard, A. Lecallier, F. Chapelet, M. Abgrall, G. Rovera, P. Laurent, P. Rosenbusch, S. Bize, G. Santarelli, A. Clairon, P. Lemonde, G. Grosche,B. Lipphardt, H. Schnatz, Eur. Phys. J. D **48**, 11–17 (2008); DOI: 10.1140/epjd/e2007-00330
[25] G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonneau, A. Clairon, O. Lopez, A. Amy-Klein, Ch. Chardonnet, Conference on Lasers and Electro-Optics, 2007. CLEO 2007. 6-11 May 2007 Page(s):1 – 2; DOI: 10.1109/CLEO.2007.4452577
[26] J. Friebe, A. Pape, M. Riedmann, K. Moldenhauer, T. Mehlstäuber, N. Rehbein, C. Lisdat, E.M. Rasel, W. Ertmer, H. Schnatz, B. Lipphardt, G. Grosche, Physical Review A **78** 033830 (2008)
[27] to be published