

## **Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 55064 - MJD 55084**

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 55064, 0:00 UTC and MJD 55084, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H5, BIPM code 1400590, using a 5 MHz phase comparator.

The relative short-term frequency instability of CSF2 was  $2.6 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$  during the 20 days. As has been demonstrated by internal comparisons with PTB-CSF1 the assumption of white frequency noise for the calculation of the statistical measurement uncertainty of CSF2 is valid at least down to  $u_A = 0.70 \cdot 10^{-15}$  at 130000 s measurement time. Currently we take this number as an upper limit for the statistical uncertainty of the whole measurement interval of CSF2.

The frequency comparison over the 20 day average is made with a statistical uncertainty - due to the instrumentation - of below  $0.1 \cdot 10^{-15}$ . In total, 17224 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.7% of the 20 x 24 hours. The very small amount of dead time was entirely due to voluntary time-outs for laser checks.

From these numbers an uncertainty due to the clock link  $u_{\text{Lab}} < 0.03 \cdot 10^{-15}$  is obtained. The estimated uncertainty for the link to TAI for 20 days is  $u_{\text{TAI}} = 0.19 \cdot 10^{-15}$ .

Frequency corrections for the following effects were applied to the raw data:

- Zeeman effect (magnetic field along the atoms' trajectory),
- AC Stark effect (thermal radiation along the atoms' trajectory),
- cold collisions effect,
- gravitational red-shift effect.

The CSF2 standard uncertainty  $u_B$  is estimated as  $1.02 \cdot 10^{-15}$  ( $1 \sigma$ ) for the relevant period.

## **Table of results of CSF2 compared to hydrogen maser H5 (1400590)**

Interval of evaluation	MJD 55064, 0:00 UTC - MJD 55084, 0:00 UTC
Fractional dead time	< 0.4%
Resulting frequency difference	$y(\text{CSF2} - \text{H5}) = -31.72 \cdot 10^{-15}$
Type A uncertainty $u_A$ (1 $\sigma$ )	$0.70 \cdot 10^{-15}$
Type B uncertainty $u_B$ (1 $\sigma$ )	$1.02 \cdot 10^{-15}$
Link to clock $u_{\text{Lab}}$ (1 $\sigma$ )	$0.03 \cdot 10^{-15}$
Link to TAI $u_{\text{TAI}}$ (1 $\sigma$ )	$0.19 \cdot 10^{-15}$ (20 days)
Combined uncertainty (1 $\sigma$ )	$1.26 \cdot 10^{-15}$

### **Type A (statistical) uncertainty of CSF2**

For CSF2 we use an optical molasses configuration for loading the atoms, with orthogonal linear polarizations for each laser beam pair. The launch direction of the atoms has been aligned with <1mrad precision using the atoms as a sensor. Because of the alignment of the launch direction and because the atomic cloud temperature is below  $10^{-6}\text{K}$ , 30% of the atoms are detected after the second Ramsey interaction. For normal operation for TAI scale unit measurements, CSF2 is operated with the optimum short-term instability conditions with about  $3 \cdot 10^4$  detected atoms.

The frequency synthesis of CSF2 is the same as the one described in the evaluation of the first fountain standard CSF1 at PTB [1]. By an internal frequency comparison between CSF1 and CSF2, where the Allan standard deviation was dominated by the white frequency noise of CSF2, a  $\tau^{-1/2}$ -dependence down to  $7 \cdot 10^{-16}$  at 130000 s averaging time could be demonstrated. Therefore we use  $u_A = 0.70 \cdot 10^{-15}$  as an estimate for the statistical uncertainty of CSF2.

### **Type B (systematic) uncertainty of CSF2**

A detailed description of the PTB fountain CSF2 has been accepted for publication in a peer reviewed journal [2]. Below we report the type B uncertainty evaluation results valid for the evaluation at hand.

#### **Frequency shifts, corrections and type B uncertainties of CSF2 (parts in $10^{15}$ ):**

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	-100.49	0.06
Blackbody radiation shift	16.57	0.06
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	0.58	0.89
Cavity phase shift		0.15
AC Stark shift (light shift)		0.001
Majorana transitions		0.0001
Rabi pulling		0.0002
Ramsey pulling		0.001
Electronics		0.20
Microwave leakage		0.10
Microwave power dependence		0.40
Background pressure		0.05
Total type B uncertainty		1.02

## **References**

[1] S. Weyers, U. Hübner, R. Schröder, Chr. Tamm, A. Bauch, *Metrologia* **38** (4), pp. 343–352 (2001)

[2] V. Gerginov, N. Nemitz, S. Weyers, R. Schröder, D. Griebisch, R. Wynands, accepted for publication in *Metrologia*