PTB'S PRIMARY CLOCK CS1: FIRST RESULTS AFTER ITS RECONSTRUCTION

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Abstract

The paper describes the reconstruction of PTB's primary clock CS1 and gives first results obtained. In view of the important role of the CS1 among the primary clocks within the international network of timing laboratories, a short look to its history is also given.

INTRODUCTION

According to its definition of 1967, the SI-unit second is realized with cesium atomic clocks. About 220 commercial devices are operated in the timing centers which are linked to a worldwide network under supervision and coordination of the International Bureau of Weights and Measures. In addition, a few laboratory standards have been developed for which a complete evaluation of all potential systematic frequency-shifting effects is sought. As their specific role in the network, they enable the scale unit of the International Atomic Time, TAI, to be as close as possible to the SI second, as realized on the rotating geoid. The PTB CS1 belonged to the group of so-called primary standards of frequency and time since 1969. It was intermittently operated until 1978 and used for the steering of PTB's atomic time scale. Between 1978 and 1995 the CS1 was operated continuously as a clock. Throughout all the years it contributed with maximum statistical weight to the formation of the free atomic time scale, EAL. Of course, more important was the fact that for many years the CS1, and since 1986 also the CS2 of PTB, were the only primary clocks with a significant contribution to the steering of TAI. The CS1 standard uncertainty had been specified to $3 \cdot 10^{-14}$[1], and that of the CS2 to $1.5 \cdot 10^{-14}$[2]. Only recently, with the NIST-7[3] and the FO-1[4], were frequency standards put into operation with a smaller standard uncertainty. The performance of the PTB clocks can at best be inferred from a comparison of their rates against TAI, as depicted in Fig. 1. The reader may note the former annual variations in the rate of TAI, as well as the systematic offset between the TAI and the two clocks around 1988-1990, when the TAI steering coefficient had been kept constant for some years.

Inevitably, many components of the CS1 were subject to aging. The vacuum system, in particular, had remained untouched since 1978, including the cesium charge of the oven. Last but not not least, having developed the CS2, the CS3[5], and the CSX[6,7], some new knowledge had been acquired in the laboratory. All that motivated a careful inspection and rejuvenation of the CS1 with the aim of improving the short-term and long-term frequency instability and eventually reducing its type B uncertainty. The clock was out of service from August 1995 until February 1996. On the 29th, to be well remembered, the atomic beam was again turned on.

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THE CS1: WHAT IT WAS AND WHAT IT IS

The CS1 had served as the model for all later clock developments at PTB. The original design by G. Becker, G. Kramer, B. Fischer, and E. K. Müller[8] already allowed the frequency-shifting effects of the atomic velocity, the cesium multilevel structure, and magnetic and electric fields to be evaluated with great accuracy. It incorporated therefore:

a) an axially symmetric atomic beam system with a point beam source and a small detector on axis;

b) an axial magnetic quantization field; and

c) magnetic lenses for the state selection and velocity filtering.

After a modification of the atomic-beam-generating system around 1977[9], the atoms contributing to the clock transition signal occurred in a narrow velocity interval of about 8 m/s with a mean velocity of about 92 m/s. Fig. 2 gives an impression of the mechanical design of the CS1 as it is now. The vacuum system has been refurbished, but the atomic-beam-generating system has been kept as it was. Differing from the previous situation, the microwave cavity is now installed in the new central vacuum chamber, which at the same time serves as the support of the quantization field solenoid. The cavity consists of the central waveguide, which is similar to the one used in the CS3[5] and the two terminal parts that are of ring-shaped design, as was proposed by A. De Marchi.[10] The electronic system has been gradually improved and has been for a few years of the same kind as the one described in some detail in [5,11].

FIRST EXPERIMENTAL RESULTS

The spectrum of the seven (F=4,m) - (F=3,m) transitions recorded with the CS1 is depicted in Fig. 3, together with the clock transition signal in higher resolution. During the initial test period we operated a rather intense atomic beam and the frequency instability σ_y (τ = 1 s) is predicted to be $4{\cdot}10^{-12}$, based on the 62.5 Hz linewidth and the signal-to-noise ratio of 900 in 1 Hz bandwidth, calculated from the shot noise of the beam and the thermal detector noise. The frequency instability observed in comparison with an active hydrogen maser agrees perfectly with the predicted value.

During the assembly of the new central vacuum chamber, we shaped the magnetic field along the atomic beam path by using a set of trimming coils on both ends of the main solenoid. The final result, obtained with a field probe moved along the beam axis, is shown in Fig. 4. Later, with the atomic beam available, the (4,3) - (3,3) resonance was used to fine-tune the fields and to make the center of the central Ramsey fringe coincide with the center of the wide Rabi pedestal. Currently the difference is only 1.2 Hz, measured with a statistical uncertainty of 0.2 Hz.

One beam reversal was performed until now which yielded an end-to-end cavity phase difference of ϕ = 150 μrad. As explained in [5], the type B uncertainty component associated with the end-to-end phase difference is independent of ϕ itself. It is only dependent on:

a) the spatial distribution of the phase of the microwave field across the atomic beam diameter inside the irradiation sections of the cavity; and

b) the degree of perfection with which the atomic beam retraces its path through the cavity.

During assembly, the beam retrace was simulated and, adding all mechanical tolerances found, a beam retrace could be systematically in error by 0.2 mm. Concerning a), the use of ring-shaped terminal parts should result in a distributed phase difference reduced by at least a factor of 10, in theory[10], compared to the value in conventional cavities.[2, 5, 6] Although in previous experiments only a factor of 4 was found[12], it should nevertheless be possible to correct for the ϕ-dependent frequency shift with a type B uncertainty of well below 10^{-14}.

OUTLOOK

It is premature to make a final emphatic statement on the characteristics of the "new" CS1. By following the evaluation step by step as it was laid down in [5] and comparing with the experimental results obtained until now, there is good reason to expect the type B uncertainty of the CS1 to be 10^{-14} or slightly below. The pitfalls may lie in an insufficient shielding of microwave stray fields inside the beam tube, in Majorana transitions occurring along the beam path[7], and possibly in an unexpectedly large sensitivity of the end-to-end phase difference of the cavity to temperature.[13] These effects have to be carefully examined before the CS1 will be put into final operation as a clock again.

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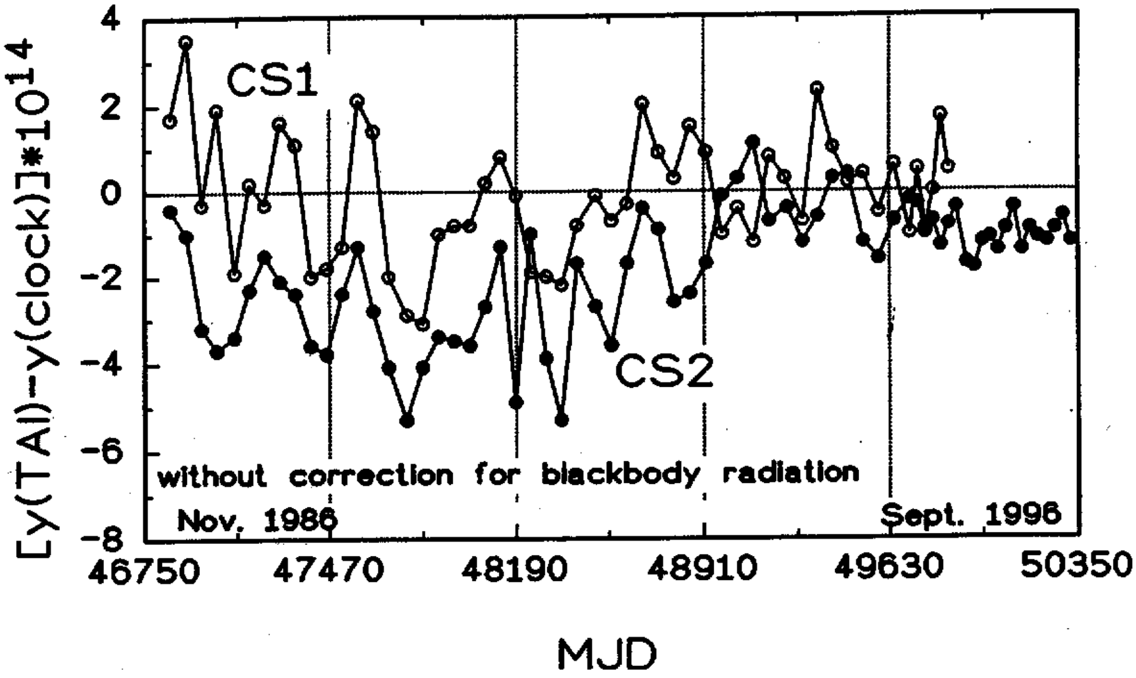

Figure 1. Ten years of frequency comparisons of the primary clocks CS1 and CS2 of the PTB with International Atomic Time, TAI. The data from BIPM Circular T are 60-day averages, the symbols are plotted at the end of each interval. MJD: Modified Julian Date.

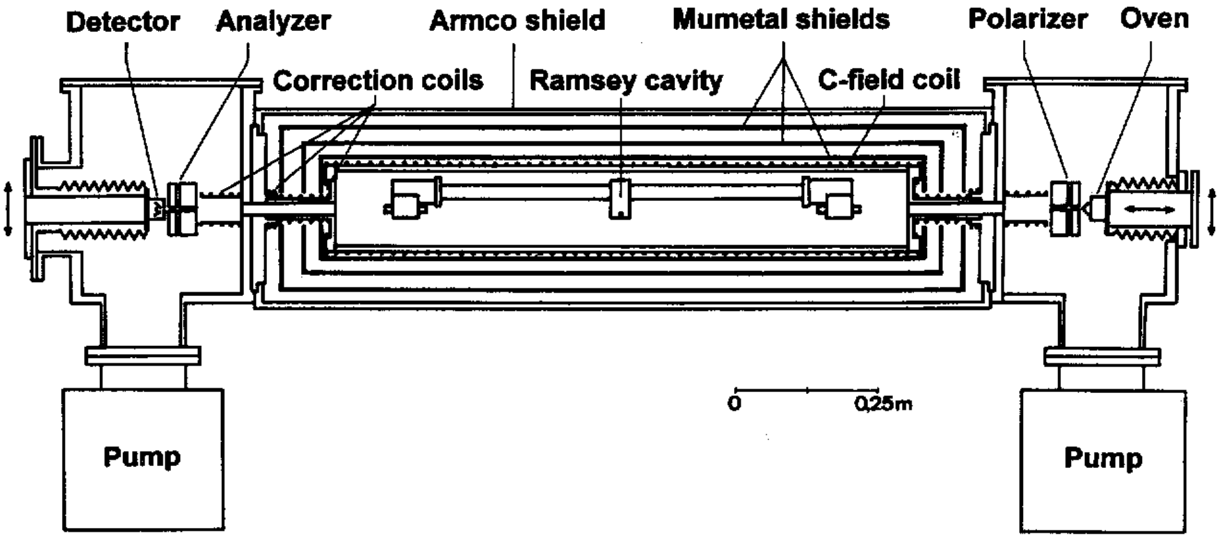

Figure 2. Vertical section through the reconstructed CS1 primary clock.

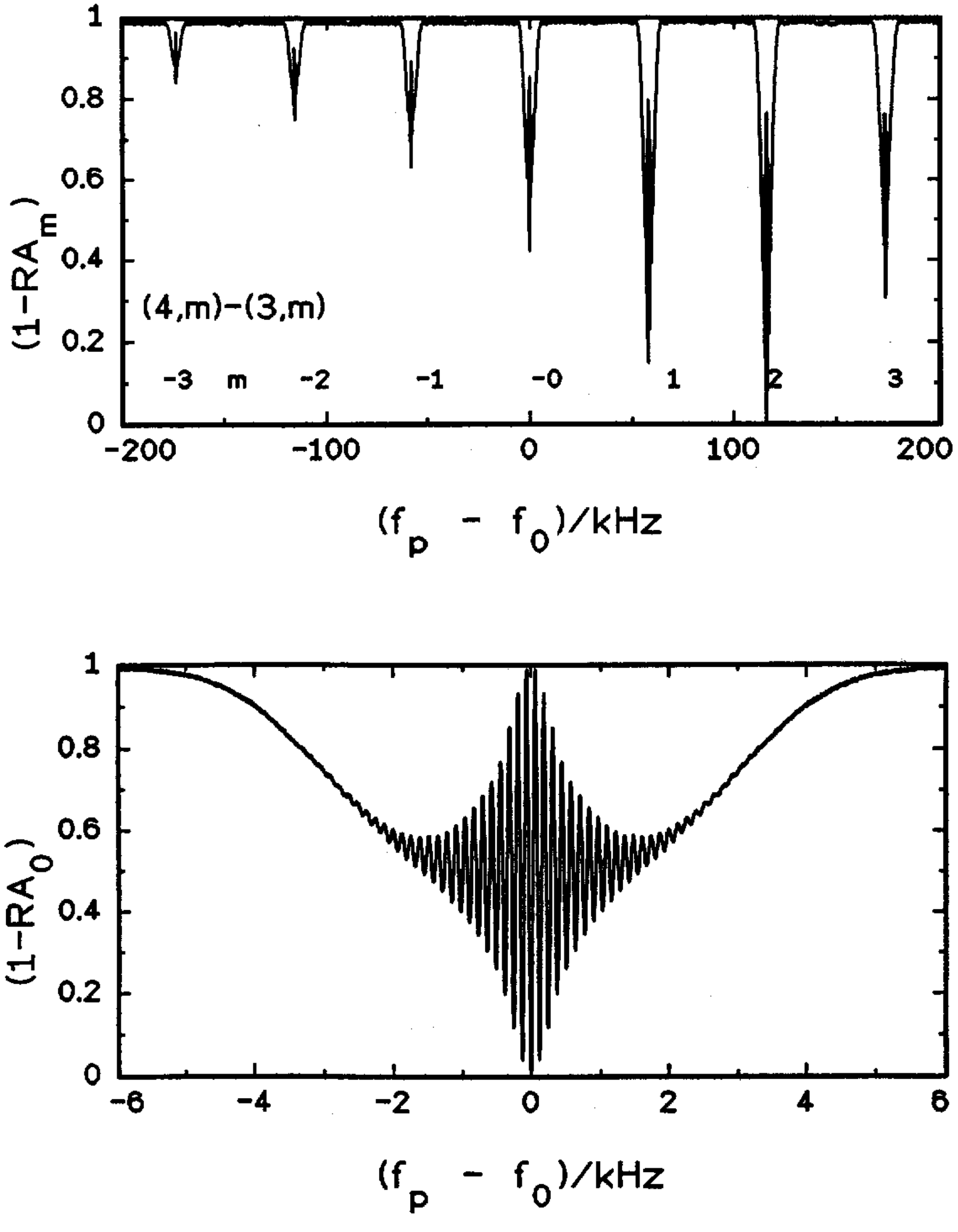

Figure 3. Microwave resonance signals recorded in the CS1. The CS1 beam optics result in an observation of the resonances in the flop-out mode; RA_m is the normalized resonance amplitude of the (4,m)-(3,m) transition; f_p - f_0: frequency detuning of the microwave probing frequency from the (4,0)-(3,0) resonance frequency f_0.
Upper graph: spectrum of the (4,m)-(3,m) transitions; the maximum of RA_2 is set to 1.
Lower graph: clock transition signal, whose maximum amplitude is set to 1.

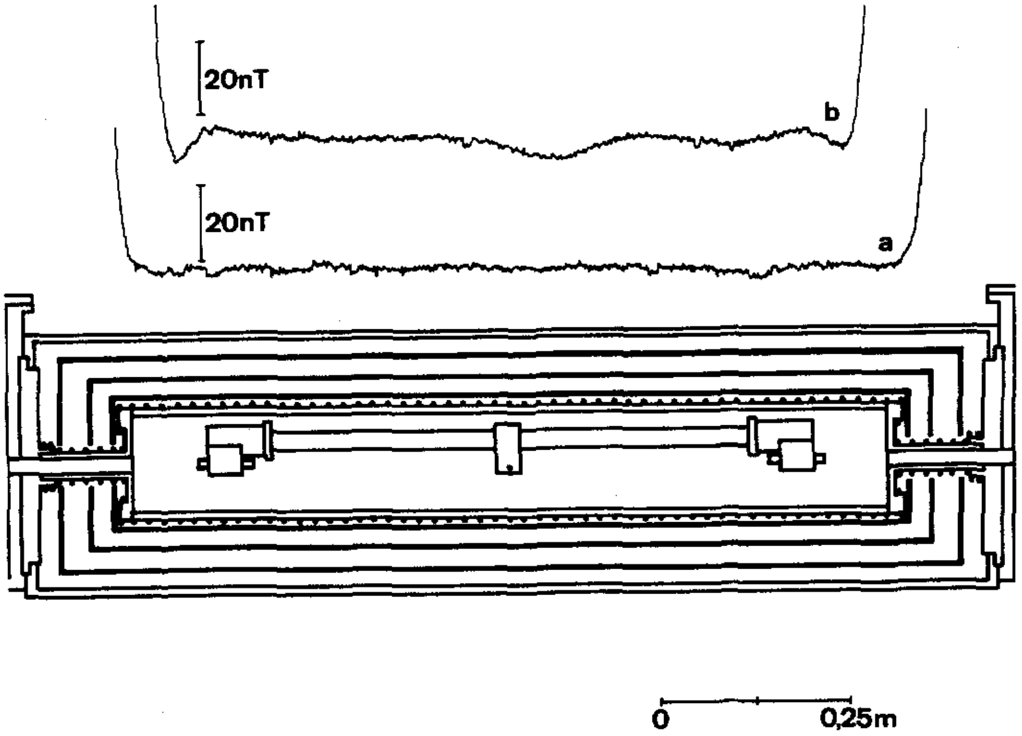

Figure 4. Plots of the axial magnetic field in the beam tube of the CS1. The position of the cavity, the magnetic shields, the solenoid and the trimming coils are shown for clarity; a) residual earth field; b) C-field after final adjustment of the current through the trimming coils, zero suppressed.

Questions and Answers

MARC WEISS (NIST): How often do you reverse the beam?

ANDREAS BAUCH: Historically, we did it every 6 weeks. Since we've operated the standard, we have done it once. So I have one measurement of the antenna phase difference, which the frequency difference in between the two directions is 5 parts in 10 to the 13th. But what we will do in the future, we have not yet decided. A couple of times per year, three or four times per year probably.