TOWARDS A CAESIUM FOUNTAIN FREQUENCY STANDARD AT THE NPL

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ABSTRACT

An experimental caesium fountain frequency standard has been constructed at the NPL. Some preliminary results obtained on this device are reported here. The experience gained in its operation is contributing to the design of a second caesium fountain which will ultimately operate as a primary frequency standard at the NPL.

1. INTRODUCTION

Since 1967 the SI second has been defined by assigning a value of 9192631770 Hz to the frequency of the transition between the two hyperfine energy levels in the ground state of the caesium atom.

Primary frequency standards based on caesium beams have been developed over many years and are now close to the ultimate limits to their performance. By exploiting the laser cooling of caesium atoms [1], the caesium fountain configuration promises further improvements in accuracy and stability of up to two orders of magnitude.

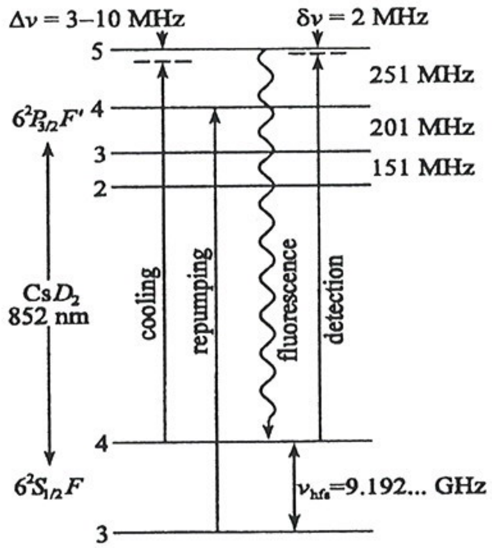

Figure 1. Energy level scheme for the caesium D_2 line, showing the hyperfine structure of each level and the transitions used in laser cooling and detection.

The first operational caesium fountain, at the Laboratoire Primaire du Temps et des Fréquences (LPTF) in Paris, has provided steering corrections to the international atomic timescale with a performance exceeding that of any other primary frequency standard. Similar fountain standards are under construction at a number of laboratories around the world [2].

Unlike a beam standard, a caesium fountain has a pulsed mode of operation. During each cycle, a cloud of typically 10^7 atoms is collected and cooled to a few microkelvin using lasers on the caesium D_2 line. The cloud is then launched upwards, passing through a cavity containing microwaves at the transition frequency, and again as it falls back under gravity. The proportion of atoms that change state due to the microwave interaction is measured by further laser beams. The microwave frequency is controlled so as to maintain the maximum number of atoms changing state.

An experimental caesium fountain frequency standard has been constructed at the NPL [3]. The cooling and launching of atoms has been investigated and the clock signal, known as Ramsey fringes, has been observed. A second caesium fountain, which will ultimately operate as a primary frequency standard, is now being developed.

Some results obtained on the experimental fountain are presented here, together with the designs for the new primary standard.

2. THE NPL EXPERIMENTAL FOUNTAIN

The experimental caesium fountain is housed in the basement of Bushy House, the 17th century mansion at the focus of the NPL site. This location provides adequate thermal stability and isolation from vibration. The purpose of this experiment is to gain experience in the assembly and operation of a device of this type.

The configuration of this fountain is shown in figure 2. The trapping and cooling chamber is in the centre, with the interaction chamber containing the microwave cavity above, and the detection region below.

Caesium atoms are cooled from a thermal vapour by six laser beams in an xyz geometry. The beams alone form a cloud of slowly-moving atoms known as an optical molasses. Applying a magnetic field gradient using a pair of anti-Helmholtz coils around the trapping chamber produces a restoring force and turns the molasses into a magneto-optical trap, or MOT. The MOT gives a higher density of cold atoms than the molasses, but generates an undesirable magnetic field, so is not used during precise frequency measurements.

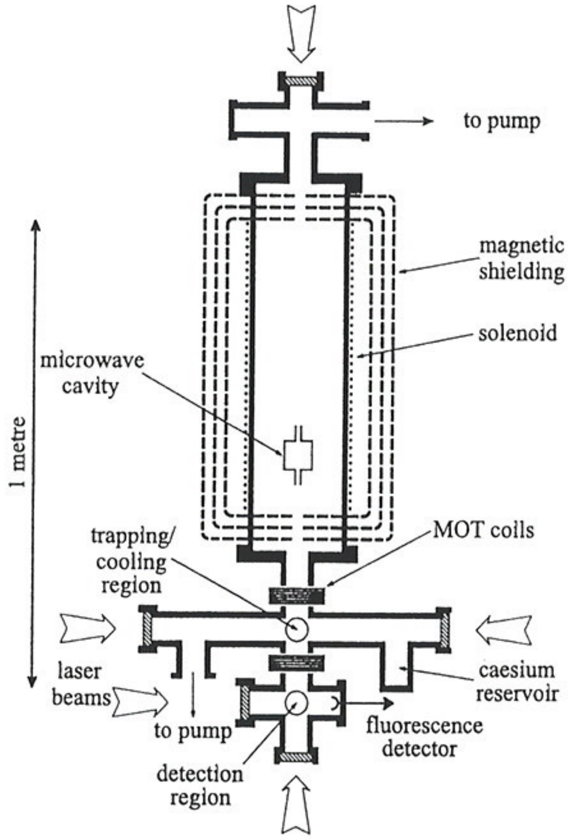

Figure 2. Schematic cross-section of the NPL experimental fountain.

The optical transitions used are shown in figure 1. The cooling beams are supplied by a pair of slave laser diodes injection locked to an extended cavity master laser. A DBR (distributed Bragg reflector) laser provides the repumping light. Polarising optical fibres give spatial filtering of the beams, as well as decoupling the alignment of the frequency control optics from that of the optics around the vacuum chamber. After launching in F = 4, a proportion of the atoms are transferred to the F = 3, $M_F = 0$ level by a 9.192 GHz pulse lasting about 7 ms. Atoms remaining in F = 4 are removed by an optical pushing pulse in the z direction.

The interaction chamber containing the TE_{011} microwave cavity is manufactured from titanium. It is temperature controlled to maintain the cavity on resonance and to stabilise the atomic frequency shift due to black body radiation. This is done by a PID controller which is gated to cut off the heating current during the time the atoms are above the microwave cavity to avoid perturbing the magnetic field. The cavity can be maintained within 50 kHz of the clock transition frequency provided that the heating due to the MOT current is kept constant over days. A solenoid wound directly onto the titanium chamber generates a uniform magnetic field, the C-field, usually of 180 nT. Three layers of mu-metal screens enclose the interaction region, with a fourth layer surrounding the entire vacuum system.

After passing twice through the cavity the atoms are detected by stimulated fluorescence. Since the number of atoms launched varies from cycle to cycle the proportion of atoms changing state must be measured. The population in F = 4 is measured by a beam on the F = 4 — F′ = 5 cycling transition before being removed by a pushing beam. The F = 3 atoms are then pumped to F = 4 and measured by F = 4 — F′ = 5 light.

The fountain sequence is controlled by a LabView program running on a PC. Sixteen analogue output channels on data acquisition boards switch the beam powers and frequencies for each phase of the cycle, as well as the MOT current, shutters, etc. The detection signals are digitised by another board. Within each cycle of typically 1.2 s duration, the sequence is hardware-timed by on-board counters using a 100 µs update interval. The microwave frequency and amplitude are controlled via GPIB.

3. THE LOCAL OSCILLATOR

A low phase noise source of microwaves is required at the "clock frequency", 9192631770 Hz. The stability of a fountain standard is affected by the phase noise, particularly close-to-carrier noise in the range of 0.1 to 10 Hz offset [4]. A microwave source has been constructed with target phase noise performance at 9.192 GHz as given in the following table.

Frequency offset from carrier (Hz)	Spectral density (dB rad^2/Hz)
0.1	-40
1	-50
10	-70
100	-75
1000	-100
10,000	-110

The close-to-carrier noise specification requires careful control of processes dominating in this region that are often seen as flicker phase noise and flicker frequency noise. In addition, a requirement for phase stability of better than 1 ps per day and 0.5 ps per K temperature change has been set.

Figure 3 illustrates the scheme adopted, which is based on a design described in ref. [5]. A dielectric resonant oscillator is phase locked in an offset scheme using a sampling down-converter and a synthesiser with millihertz resolution. The sampling down-converter is driven by a 200 MHz source derived from a pair of low noise crystal oscillators, at 5 and 100 MHz. The 100 MHz crystal is phase locked to the 5 MHz device using a double balanced mixer after a bipolar divide-by-10. The bandwidth of the locking loop (approximately 500 Hz) is chosen to give the best performance over the range of offsets in the table. The phase comparison is operated from 200 MHz so as to counter phase drift due to the frequency doublers. The 5 MHz crystal is loosely phase-locked to our local timescale frequency reference, an active hydrogen maser. This is done at 100 MHz both to improve phase sensitivity and to reduce the effect of phase drift due to the multipliers.

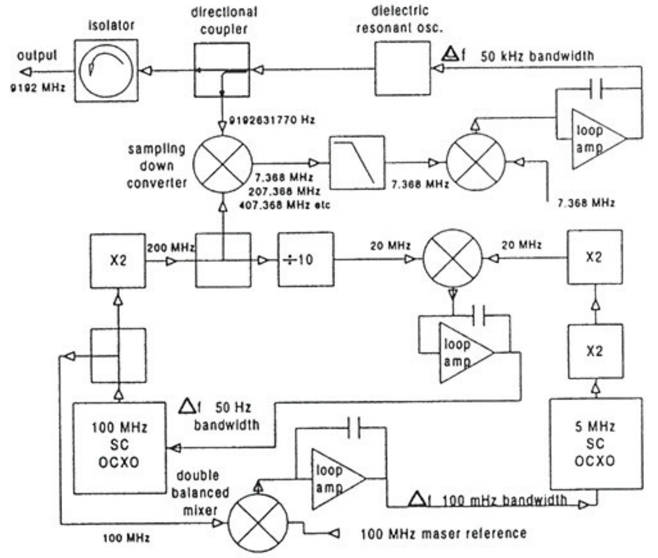

Figure 3. Representation of the low phase noise 9.192 GHz source.

4. OBSERVATION OF RAMSEY FRINGES

Two typical Ramsey fringe patterns on the $M_F = 0$ — $M_{F'} = 0$ transition are shown in figures 4 and 5. The figures show the fluorescence signal detected from atoms in F = 4 normalised to the total detected atom number. For these data the atoms are trapped using the MOT, with a field gradient at the trap centre of 80 μT/mm. The atom temperature, determined from the time-of-flight signal, is around 4 μK. The microwave frequency is stepped by 0.05 Hz between each fountain cycle and each point represents a single fountain cycle, *i.e.* there is no averaging.

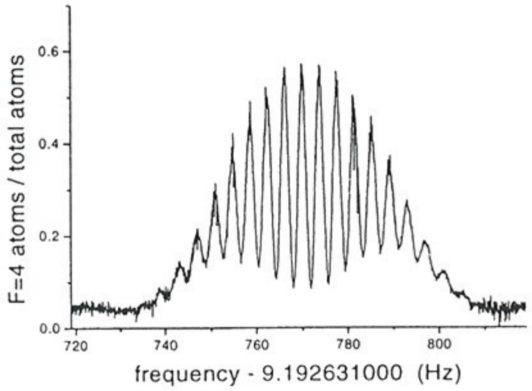

Figure 4. Ramsey fringes from atoms launched at a velocity of 2.56 m/s, corresponding to a launch height of 8 cm (time-of-flight 225 ms) above the centre of the microwave cavity. The FWHM of the central fringe is about 2 Hz.

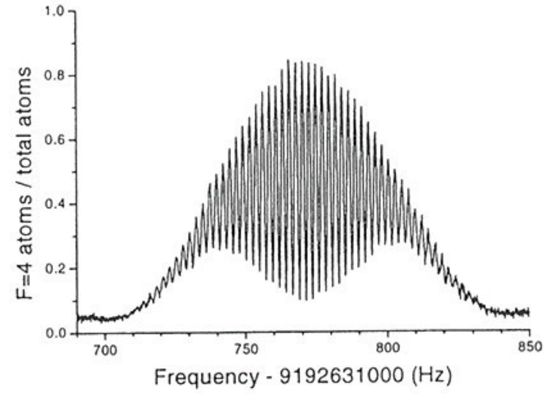

Figure 5. Ramsey fringes from atoms launched at a velocity of 3.10 m/s, corresponding to a launch height of 22.5 cm (time-of-flight 430 ms) above the centre of the microwave cavity. The FWHM of the central fringe is 1.2 Hz.

5. THE NPL PRIMARY STANDARD

A second caesium fountain is under construction at the NPL. A major design consideration is that its sources of frequency shifts can be measured and corrected for, so that it can ultimately operate as a primary frequency standard.

Figure 6 illustrates the vacuum system. The interaction chamber is being constructed from aluminium alloy, which is non-magnetic, and other components will utilise low-permeability materials. Three layers of magnetic shielding will surround the interaction chamber, as in the experimental fountain, and this region will be temperature-stabilised.

The trapping chamber is located at the bottom to give maximum separation between this region, where caesium atoms are cooled from a vapour, and the interaction chamber in which a low caesium background pressure is desirable. Three counter-propagating pairs of cooling beams enter the trapping chamber via fibres at 35.3° to the horizontal, in the (111) geometry. This configuration avoids the need for a cooling beam along the z axis, which would be constrained in diameter by the apertures in the microwave cavity.

The central detection chamber has four large-diameter windows for the detection beams and fluorescence detection optics, as well as ports for pumping and for microwave feedthroughs. Between the trapping and detection chambers is an additional small chamber with dimensions corresponding to the TE_{011} mode at 9.192 GHz. A microwave pulse in this chamber prepares the launched atoms in the $F = 3$, $M_F = 0$ state.

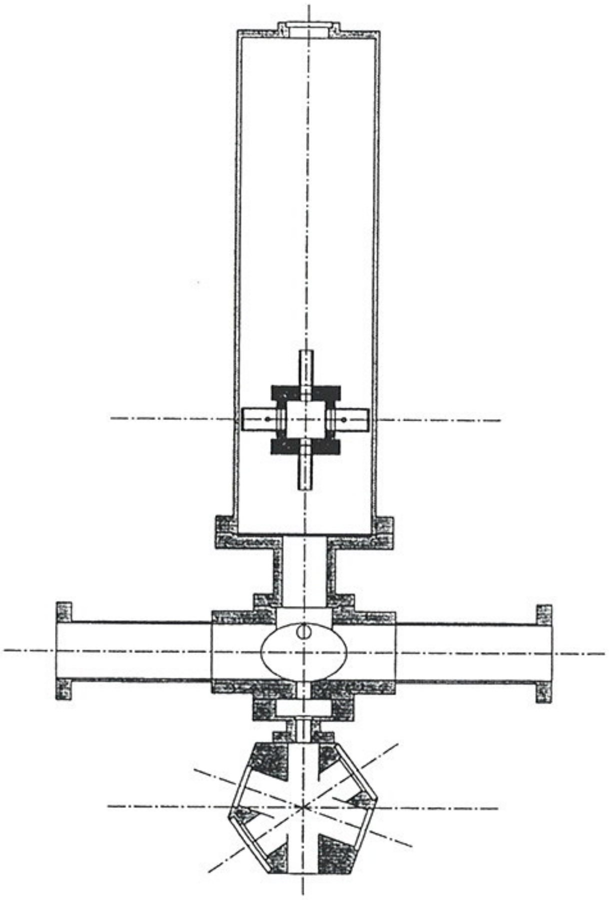

Figure 6. Diagram of the vacuum system of the NPL primary frequency standard.

The fountain primary frequency standard will be assembled in the new NPL building, in a module which will be ready for occupation during mid-2000. This will provide better temperature stability and vibration isolation than the present location, and a comparable level of ambient magnetic field.

The short-term stability of the primary standard is expected to be better than $1 \times 10^{-13}\ \tau^{-1/2}$, and its accuracy around 1×10^{-15}.

6. REFERENCES

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[2] A. Clairon et al., "A cesium fountain frequency standard: preliminary results", IEEE Trans. Instrum. Meas., 44 (2), 128-131, April 1995.

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[5] G. D. Rovera, G. Santarelli and A. Clairon, "Frequency synthesis chain for the atomic fountain primary frequency standard", IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, 43 (3), 1996.

ACKNOWLEDGEMENT

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