

## NIST CESIUM FOUNTAIN MICROWAVE CAVITIES

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## Abstract

The cesium fountain under development at the NIST Time and Frequency Division contains two identical microwave cavities, one used for state selection and the other for Ramsey excitation. These cavities, designed to hold distributed cavity phase shift to a minimum are described and data relevant to the designs of such cavities presented.

## Introduction

Laser cooled cesium fountains are in operation<sup>1</sup>, under development, or being planned, in a number of laboratories all over the world. A significant advantage of the fountain geometry relative to that of a traditional thermal beam device is the absence of a systematic frequency shift caused by an end-to-end phase shift in the microwave structure<sup>2</sup>. In the fountain geometry atoms receive the two Ramsey ( $\pi/2$ ) pulses in the same microwave cavity<sup>3</sup> thereby eliminating a possible phase difference between the two ends of the traditional microwave structure. However, the laser-cooled atoms typically used in cesium fountains have a residual temperature of about 5 $\mu$ K, and the resulting velocity (about 2 cm/s) causes atom loss along the apertures into and out of the microwave cavity as well as changing the position of the atom relative to the aperture between the two Ramsey interrogations. These apertures are typically the major source of atom loss in the fountain and are therefore made as large as possible. These large apertures can lead to a systematic frequency shift if the phase of the microwave field is a function of position within the aperture. This distributed cavity phase has been carefully modeled for the cavities considered here and the results are discussed below.

The cavity system described here consists of two separate, nominally identical, TE<sub>011</sub> cavities as seen in Figure 1. The lower of the two cavities is used for state selection and the upper for Ramsey excitation.

If the atomic sample is distributed in all  $m$  states (the situation in a typical sample of cesium atoms launched from optical molasses) then the majority of the atoms will not contribute to clock signal on the  $m=0$ ,  $\Delta m=0$  transition and it is advantageous to remove atoms not in the  $m=0$  state. This can be accomplished with a microwave  $\pi$  pulse resonant on the  $|F=4, m=0\rangle$  to  $|F=3, m=0\rangle$  transition followed by an optical pulse resonant on  $F=4 \rightarrow F=5'$ . Then all atoms remaining are in  $|3, 0\rangle$ . The  $|3, 0\rangle$  atoms then enter the second

microwave cavity where the initial Ramsey excitation is performed.

## Physical Description of the Cavities

The cavities used in this fountain are constructed of oxygen-free high conductivity copper (OFHC) and the various parts are brazed together forming a vacuum tight structure which is part of the vacuum vessel for the fountain. The entrance and exit apertures are 1 cm in diameter, centered on the cavity axis and have a length of approximately 10 cm. Both cavities are fed by resonant mode-filter cavities with a total of four feeds. This arrangement was adopted to provide both a large number of feeds, which helps to reduce distributed cavity phase shifts, and to provide as pure an excitation of the TE<sub>011</sub> mode as possible. The cavity radius is 3 cm and the height is 2.18 cm. These dimensions, while not optimum from the standpoint of the unloaded Q of the cavity, are helpful in reducing the distributed cavity phase shift, as well as decreasing the ratio of time spent in the microwave cavity to time spent in the microwave field-free region.

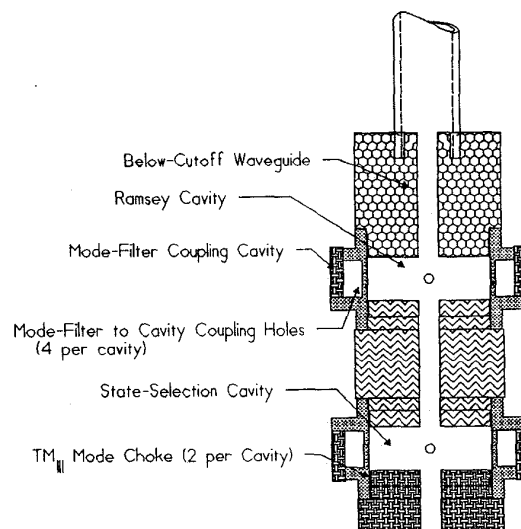


Figure 1 - A cross-sectional view of the NIST Cs. Fountain cavities with many of the relevant details labeled.

The  $TE_{011}$  mode used in these cavities is, unfortunately, degenerate with the  $TM_{111}$  mode and this later mode must be suppressed in order to avoid exciting  $\pi$  transitions in the cesium atoms. This mode is both suppressed and shifted in frequency in these cavities by the use of  $1/4$  wave chokes at each end of the microwave cavity.

The mode-filters which drive the central  $TE_{011}$  cavities are rectangular cross-section waveguide cavities one wavelength long at 9.192 GHz with an "a" dimension (the longer side of the rectangle) of 1.83 cm and with "b" = a/2. The mode-filters are coupled to the microwave synthesizer using a vacuum feedthrough which has a loop antenna at one end of the mode filter. The loaded Q of the mode filter is approximately 4000 and its resonant frequency is centered on the cesium transition at 9.192 GHz. The mode-filters feed the central cavity through 4.5 mm diameter apertures located at  $90^\circ$  intervals around the periphery of the cavity, centered on the vertical extent of the cavity.

The theoretical Q for the central  $TE_{011}$  cavity is 22,000 while the measured loaded  $Q_L$  is  $21,500 \pm 500$ . The cavity insertion loss in transmission through the cavity driving one mode filter while using the other as an antenna is about 60dB, so the agreement of the loaded and theoretical unloaded Q is to be expected.

### Distributed Cavity Phase

The phase of the microwave field across the entrance and exit apertures is, as mentioned earlier, of crucial interest in an atomic fountain frequency standard. The number of microwave feeds has a direct impact on the phase flatness across the aperture, with a simple geometric argument suggesting that the phase deviation,  $\delta\xi$ , should scale as

$$\delta\xi \propto \left[ \frac{r_a}{r_c} \right]^{n_f} \cos(n_f * \phi)$$

where  $r_a$  is the radius of the aperture,  $r_c$  is the radius of the microwave cavity,  $n_f$  is the number of microwave inputs to the cavity and  $\phi$  is the azimuthal coordinate in cylindrical coordinates. The resulting distributed cavity phase is illustrated in Fig. 2, and is, in fact, is a good qualitative fit to numerical simulation results discussed later in the paper. This result, suggests that relatively short, large-diameter microwave cavities with multiple feeds will have better distributed cavity phase than cavities with more nearly equal diameter and height and fewer microwave feeds. However, this is oversimplified, as other modes supported by the cavity will also cause the same sort of phase-deviations and these other modes must also be considered in the design.

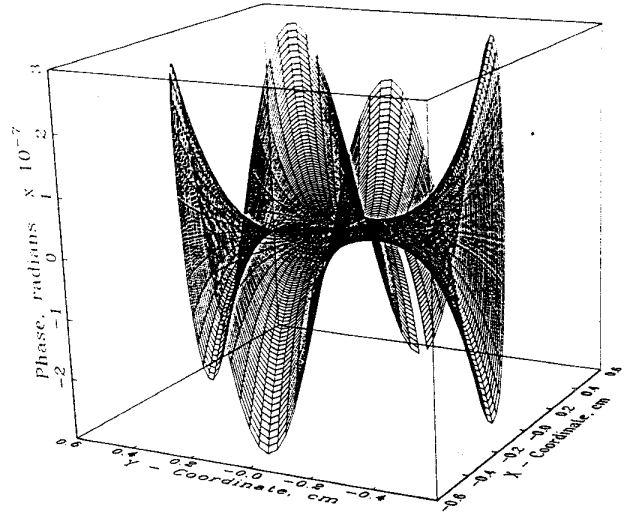


Figure 2 - A plot of Equation 1 multiplied by an overall constant to fit it to the numerical modeling results shown in Fig. 3.

We have also performed finite element analysis of these cavities in order to carefully examine the distributed cavity phase and the results are shown in Fig 3. The maximum phase deviation at the edge of the aperture is 0.34  $\mu$ radians. This leads to a worst case frequency shift for an atom which sampled +0.34  $\mu$ radians on the way up through the cavity and -0.34  $\mu$ radians on the way down of less than  $10^{-16}$ , assuming normal Ramsey times of greater than 100 ms. This is clearly the worst case as most of the atoms traversing the aperture cannot sample the extrema in the phase. In fact, a study of the phase patterns shown in Figs. 2 and 3 suggests that atoms should quite efficiently average the distributed cavity phase shift to much less than 0.34  $\mu$ radians.

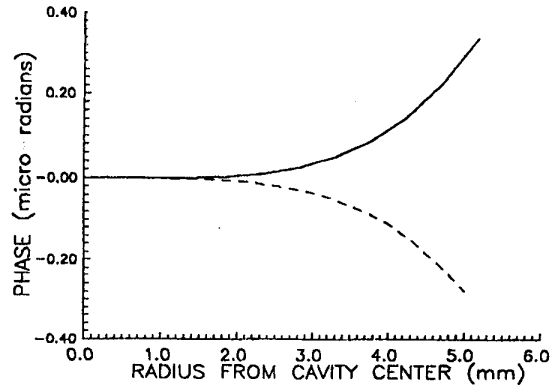


Figure 3 - The phase excursion along the direction of a microwave feed (solid line) and half way between the microwave feeds (dotted line) as calculated using a finite element modeling approach.

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### References

1. The L.P.T.F is currently operating a cesium fountain as a primary frequency standard reporting to the BIPM, see the paper by E Simon, G Santarelli, Ph. Laurent, S. Ghezali, P. Lemonde and A. Clairon in these proceedings. Cesium fountains are under development in at least the following countries: Canada, United States, Germany, Italy, Japan, Taiwan, Peoples Republic of China, Brazil and England. This list is almost certainly not complete.
2. J. Vanier and C. Audoin, "*The Quantum Physics of Atomic Frequency Standards*", Adam Hilger, Bristol 1989, pp 699.
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