# Hydrogen maser magnetron cavity with sub-kHz/°C frequency-temperature coefficient

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We identify a key dimensional parameter in the geometry of the hydrogen maser magnetron cavity and its inner bulb that allows one to set down deterministically the frequency-temperature coefficient (FTC) of the atomic clock cavity in the sub-kHz/C range, while keeping the cavity within its operational range of parameters for proper clock operation (good quality factor and suitable resonance frequency). The target cavity geometry is obtained from thermal expansion simulations using a finite element method [1].
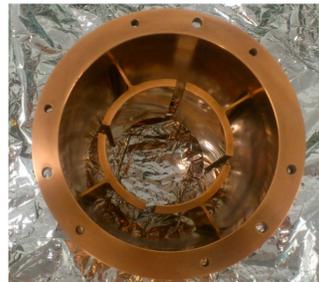
Hydrogen maser: scheme of principle

H ground state

$1s_{1/2}$

$F = 1$

1420 MHz

$F = 0$
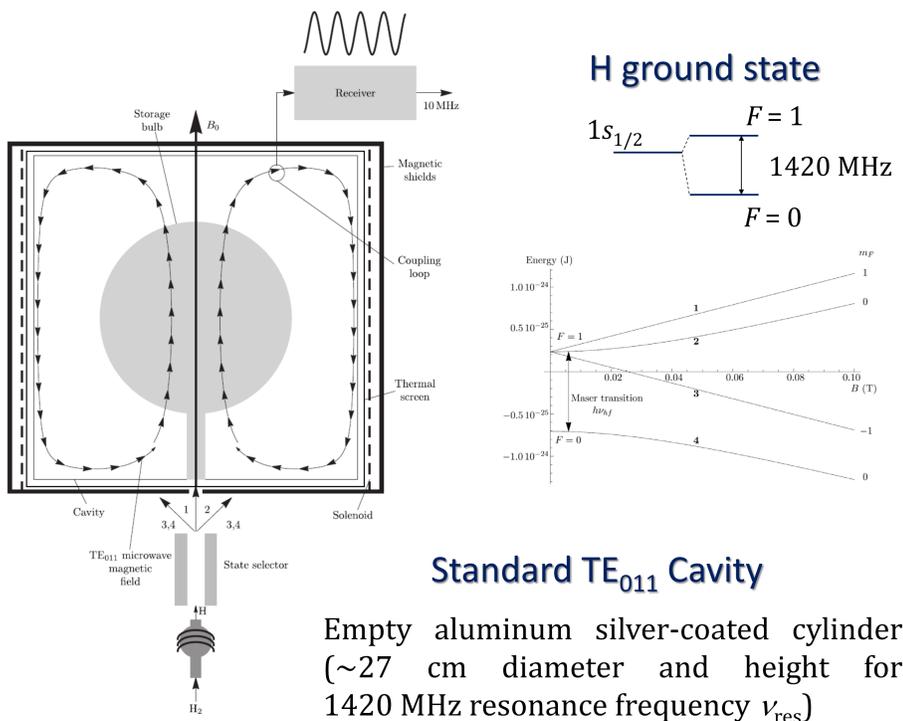
Standard TE$_{011}$ Cavity

Empty aluminum silver-coated cylinder ($\sim$27 cm diameter and height for 1420 MHz resonance frequency ν_{res})

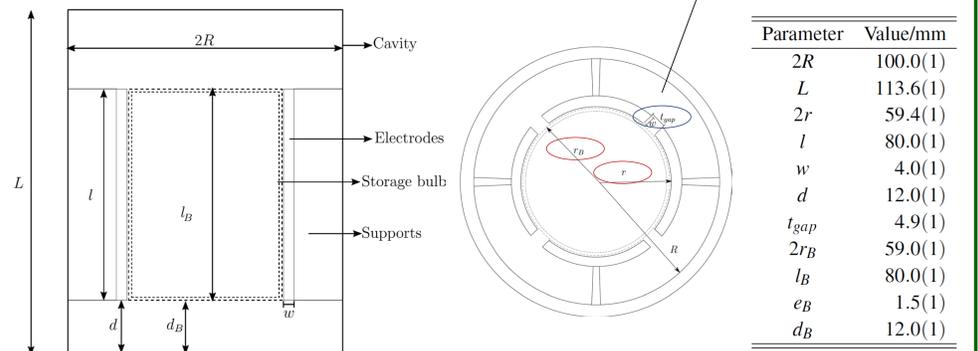$\longrightarrow$ heavy and non compact

Weight and compactness issue and can be adressed using **magnetron-type** cavities (cylindrical cavity + 4 inner electrodes)
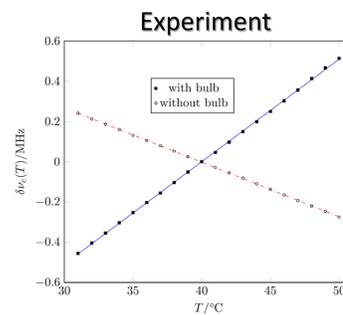
Good for space applications

Frequency-temperature coefficient (FTC)

Cavity resonance frequency ν_{res} is temperature dependent

$\rightarrow$ Linear dependence   FTC = linearity coefficient

$$\Delta \nu_{\mathrm{res}} = \mathrm{FTC}\, \Delta T$$

Ideal FTC value

- 0 for optimal clock stability (clock transition frequency insensitive to thermal fluctuations)
- A few kHz/°C to keep a thermal control of ν_{res}

Standard TE$_{011}$ Cavity

FTC $\sim$ -30 kHz/°C

$\longrightarrow$ No way to tune it

Magnetron-type Cavity

FTC strongly dependent on the presence or not of the hydrogen storage bulb, can be very low using distinct electrode materials [2]

Can only be theoretically modeled using finite element analysis (FEM) solver $\longrightarrow$ Comsol Multiphysics® [3]

Magnetron-type cavity FTC simulations

Considered geometry parameters

for ν_{res} tuning

Parameter	Value/mm
$2R$	100.0(1)
L	113.6(1)
$2r$	59.4(1)
l	80.0(1)
w	4.0(1)
d	12.0(1)
t_{gap}	4.9(1)
$2r_B$	59.0(1)
l_B	80.0(1)
e_B	1.5(1)
d_B	12.0(1)

Experimental and simulation results

Experiment

Storage bulb	FTC/kHz °C^{-1} FEM study	Experiment
With	40(12)	50.9(2)
Without	$-27.10(85)$	$-27.06(6)$

Parameter	σ_{FTC}/kHz °C^{-1} without bulb	with bulb
LSF	0.0010	0.19
α_{Co}	0.82	1.2
$2R$	0.013	0.17
L	0.0083	0.056
$2r$	0.024	8.3
l	0.0031	0.11
w	0.12	0.68
d	0.0048	0.036
t_{gap}	0.17	0.37
α_{quartz}	–	0.12
ε_r	–	1.3
$2r_B$	–	8.4
l_B	–	0.037
e_B	–	2.2
d_B	–	0.24
Altogether	0.85	12

Uncertainty contributions (LSF = least-square fit)

Magnetron-type cavity FTC vs interstice

FTC is highly sensitive to the interstice parameter $e_i = r - r_B$ (space between bulb and inner electrodes)

$\longrightarrow$ **Key parameter to tune FTC !**

FEM Simulations
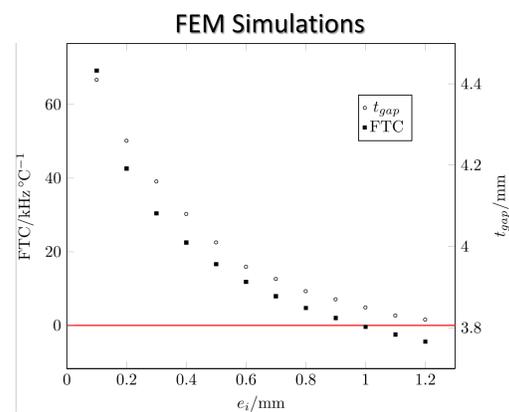
Gap between electrodes adapted to keep resonance frequency close to 1420 MHz to within 1 MHz

Cavities can be machined to any desired FTC value at a practical resolution of about 0.2 kHz/°C

Complete FTC tunability between 0 and 50 kHz/°C over 1 mm of variation of e_i !!

FTC = -0.4(1.0) kHz/°C @ ei = 1.00(5) mm

$\longrightarrow$ Not surprising in view of the electric field distribution inside the cavity (interaction with bulb dielectric maximal near electrodes):

Electric field distribution inside the cavity
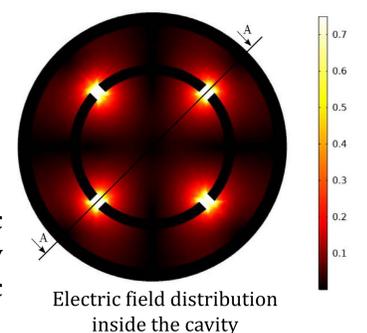
References

[1] E. Van der Beken, D. Léonard, and T. Bastin, Metrologia **59**, 035006 (2022) & patent application PCT/EP2022/077947.

[2] H. Chen, J. Li, Y. Liu, and L. Gao, Metrologia **49**, 816 (2020).

[3] COMSOL Inc. Comsol Multiphysics (version 5.6). Burlington, MA, 2021.