A STUDY OF HYDROGEN MASER RESONATORS AND STORAGE BULBS FOR USE IN GROUND AND SATELLITE MASERS *

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I Introduction

Experiments using hydrogen masers in rocket probes and earth-orbiting satellites have motivated the design of small, light-weight, rugged masers. Masers now in laboratory use typically weigh 275 kg (600 lb) and occupy 0.6 m^3 (20 ft^3) or more. Smaller masers, weighing 41 kg (89 lb), have been built for a rocket-borne gravitational red-shift experiment.[1] These may be the forerunners of still smaller space masers that will utilize new technology and novel cavity designs.

Traditional masers use a cylindrical TE_{011}-mode resonant cavity in which is mounted a spherical or ellipsoidal fused-quartz bulb (Fig. 1). The bulb confines the hydrogen atoms to a region in which the longitudinal component of the oscillating magnetic field is uniform in phase and direction. Its interior surface is coated with Teflon to reduce interactions between the hydrogen atoms and the bulb wall. A typical TE_{011} maser cavity, resonant at the hydrogen hyperfine frequency f_{hfs} = 1420.405 MHz, is approximately 28 cm (11 inches) in diameter and 25.4 cm (10 inches) long. The cavity dimensions determine the minimum size, and hence weight, of the surrounding vacuum tank and magnetic shields. In order to make masers smaller, lighter, and more rugged, it is desirable to reduce the size of the cavity and to eliminate the separate quartz bulb. These changes would have several added benefits. The smaller size would decrease the power required

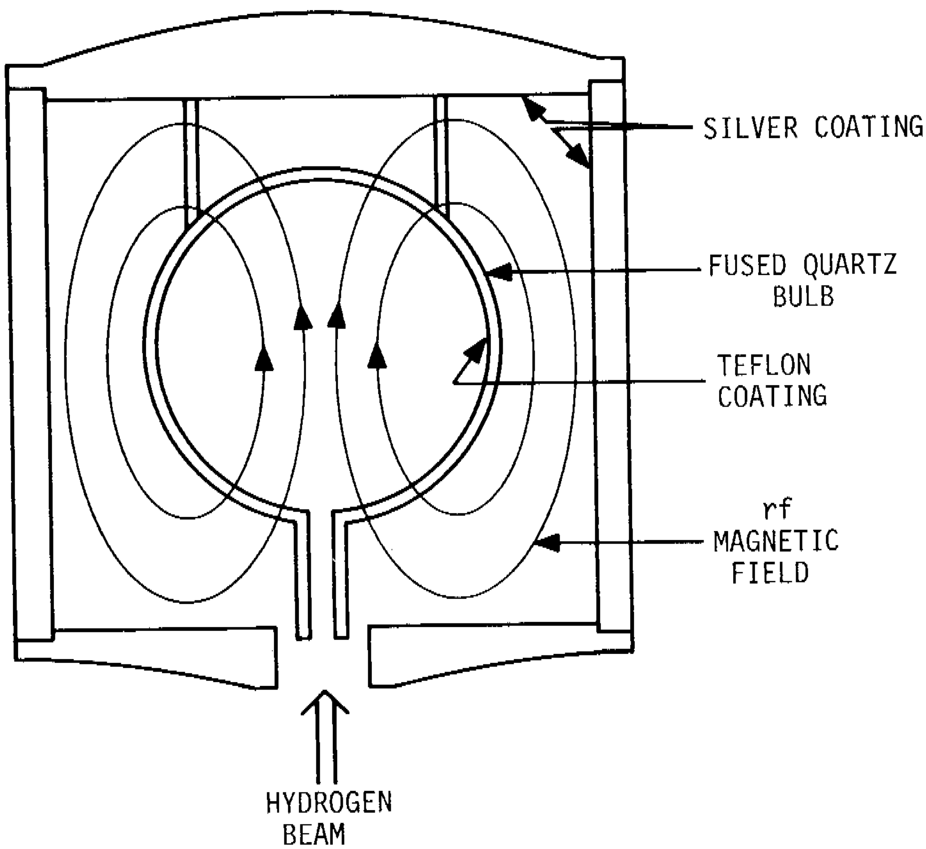

Fig. 1 Conventional TE_{011}-Mode Maser Cavity

by the temperature control circuits, improve thermal control of the cavity by reducing temperature gradients, and permit the use of optimally shaped magnetic shields in a smaller space. Eliminating the bulb would increase the cavity Q and decrease the maser's sensitivity to temperature changes by removing dielectric material from within the resonator.

We have proposed[2,3] two general designs for small bulbless maser cavities, and have constructed examples for tests. The first design employs a cylindrical TE_{011} or spherical TE_{101} cavity with thick dielectric walls (Fig. 2). The walls, which are coated on the outside with silver to form the electromagnetic resonator and on the inside with Teflon to form the atom-confining boundary, load the cavity, making it smaller than an unloaded cavity resonant at the same frequency. At the same time they form a bulb that is integral with the cavity, creating a rugged, monolithic structure.

The second proposed type of small maser cavity (Fig. 3) uses an unloaded resonator supporting either the rectangular TE_{101} or the cylindrical TE_{111} mode. A thin septum divides the cavity into two regions of oppositely directed oscillating magnetic field, and splits the entering hydrogen beam so that half of the atoms go into each region. The interior surfaces of the cavity are coated with Teflon, and the septum is made of sheet Teflon or of thin Teflon-coated material.

Not all cavity-bulb structures can support self-oscillation. The power radiated by the incoming hydrogen atoms must exceed the losses in the cavity. This places a lower limit on the cavity Q, and also on the strength of the oscillating magnetic field stimulating the atoms. In the next section we describe a new oscillation criterion that takes into account the field distribution in the cavity, the geometry of the atom-confining region, and the conductivity of the

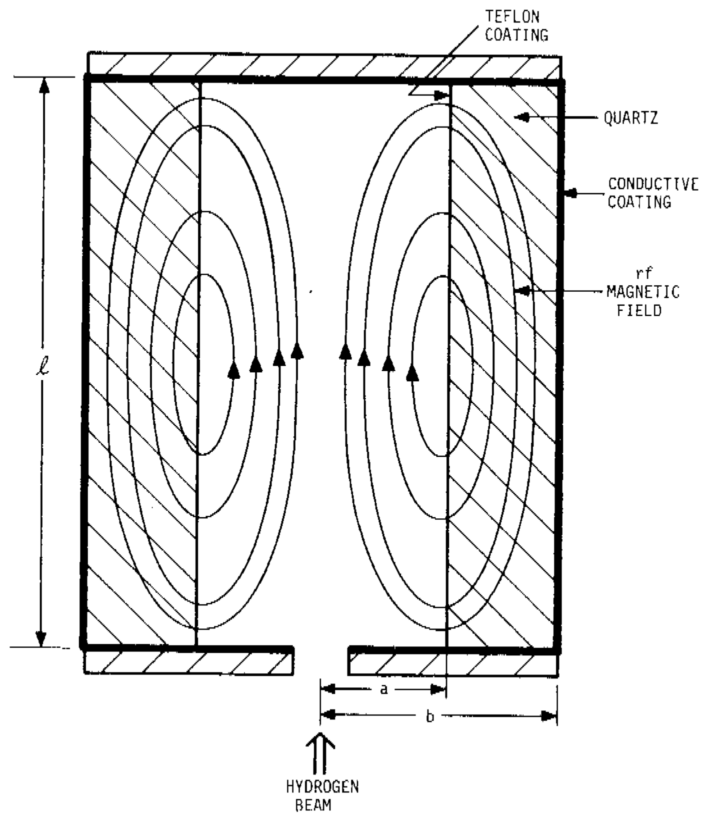

Fig. 2a Cylindrical TE_{011} Dielectric-Loaded Maser Cavity

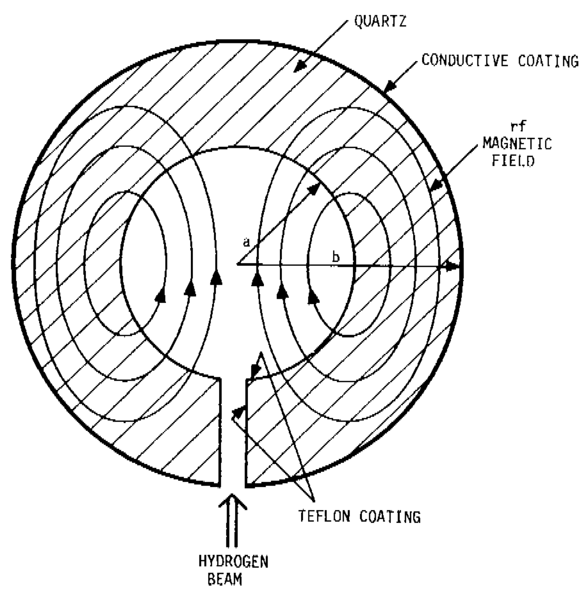

Fig. 2b Spherical TE_{101} Dielectric-Loaded Maser Cavity

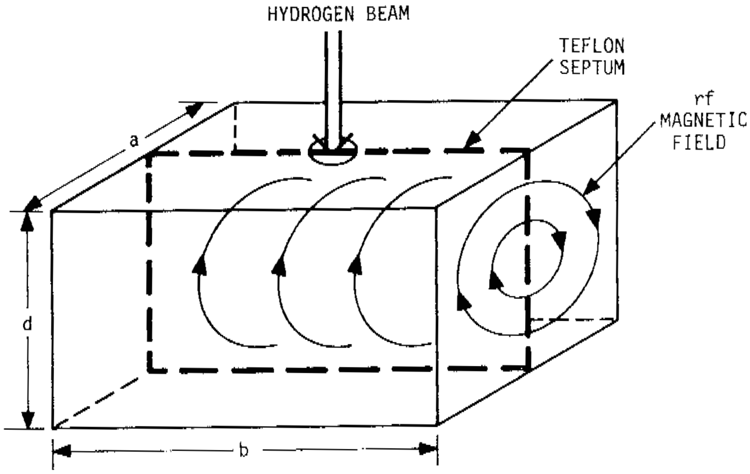

Fig. 3a Rectangular TE_{101} Septum Maser Cavity

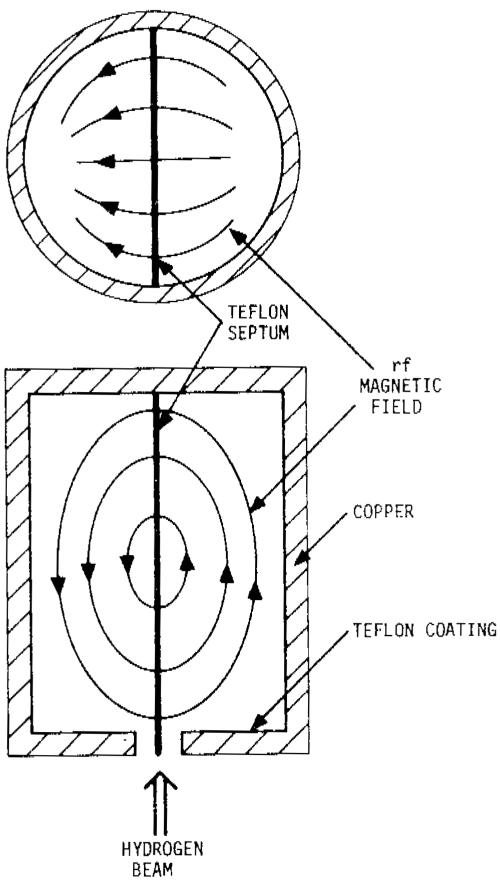

Fig. 3b Cylindrical TE_{111} Septum Maser Cavity

cavity walls. In succeeding sections we use this measure to evaluate the feasibility of the proposed small maser cavities.

II Maser Oscillation Criterion

It has been shown[4] that the following inequality must be satisfied if a single-bulb maser is to sustain oscillation:

$$q \equiv \left[\frac{\sigma \bar{v}_r \hbar}{8\pi\mu_o^2}\right] \cdot \frac{\gamma_t}{\gamma_\ell} \cdot \frac{I_{tot}}{I} \cdot \frac{V_c}{V_b} \cdot \frac{\langle H^2 \rangle_c}{\langle H_z \rangle_b^2} \cdot \frac{1}{Q} \leq 0.172 \qquad (1)$$

Here

μ_o = Bohr magneton

$\bar{v}_r$ = average relative velocity of hydrogen atoms in bulb

σ = hydrogen-hydrogen spin-flip crossection

Q = loaded Q of cavity

I_{tot} = total H atom flux entering bulb

I = flux of H atoms entering bulb in $F = 1$, $M_F = 0$ state

V_b = volume of bulb

V_c = volume of cavity

$\langle\ \rangle_b$ = average over bulb volume

$\langle\ \rangle_c$ = average over cavity volume

H_z, H^2 = oscillating magnetic field in cavity

γ_t = total density-independent hydrogen relaxation rate (excludes spin-exchange relaxation)

γ_ℓ = rate of loss of hydrogen atoms from bulb

The notation of Eq. 1 differs from that of Ref. 4 to emphasize that γ_ℓ does not equal the geometrical escape rate γ_b of atoms from the bulb. Implicit in the quantity q is the hydrogen atom density in the bulb, which is determined by the balance between the rate at which H-atoms enter the bulb and the total rate at which they are lost. The loss mechanisms include escape through the bulb's aperture, recombination on the bulb's wall to form hydrogen molecules, and adsorption on or chemical combination with the wall. Escape and recombination are the dominant loss mechanisms contributing to γ_ℓ, and it has been shown experimentally[5] that to a good approximation

$$\gamma_t / \gamma_\ell = 1 \tag{2}$$

The quantities in square brackets in Eq. 1 depend upon properties of the hydrogen atom; for a cavity temperature of 50 C, their values[4] give

$$\frac{\sigma \bar{v}_r \hbar}{8\pi \mu_c^2} = 510 \tag{3}$$

The type of state selector used in present hydrogen masers focuses into the cavity equal numbers of atoms in the states F = 1, m_F = 1 and F = 1, m_F = 0, making

$$I_{tot}/I = 2 \tag{4}$$

Combining Eqs. 2, 3, and 4 with Eq. 1 gives the following criterion[6] for maser oscillation:

$$S \equiv Q\eta' \geq 5.9 \times 10^3 \tag{5}$$

where

$$\eta' \equiv \frac{V_b}{V_c} \frac{\langle H_z \rangle_b^2}{\langle H^2 \rangle_c} \tag{6}$$

η' is called the bulb filling factor. The oscillation criterion for a septum cavity is the same as Eq. 5, but the filling factor is defined by

$$\eta' = \frac{2V_b}{V_c} \frac{\langle H_z \rangle_b^2}{\langle H^2 \rangle_c} \tag{6b}$$

where V_b is the volume of a single bulb region (equal to half of the cavity volume) and $< \;>_b$ is an average over one bulb region. We emphasize that it is the quantity S, and not the cavity Q or the filling factor alone, that determines the ability of a given cavity and bulb to support maser oscillation.

Because the amount of power coupled from the cavity is not known a priori, we define

$$S_o = Q_o \, \eta' \qquad (7)$$

where Q_o is the unloaded cavity Q. S_o and S are related by

$$S = \frac{S_o}{1 + \beta} \qquad (8)$$

where β is the cavity's external coupling factor.

III Dielectric-loaded Cavities

Cylindrical Cavity

A cylindrical loaded cavity, which resembles conventional maser cavities and which would be simple to fabricate and tune, is shown in Fig. 2. Graphs of S_o as a function of cavity dimentions are shown in Fig. 4. The graphs indicate that for a dielectric loss tangent δ = 6×10^{-5} the threshold condition on S cannot be satisfied by any cylindrical cavity of practical shape. We have calculated the maximum permissible loss tangent for a quartz cylindrical cavity with ℓ/b = 2.4, $a/b = 0.5$ (a = 3.95 cm, b = 7.00 cm, and ℓ = 18.95 cm), assuming the most favorable conditions found in practice: $\beta = 0.1$, and actual Q equal to 70% of the theoretically calculated Q. With an

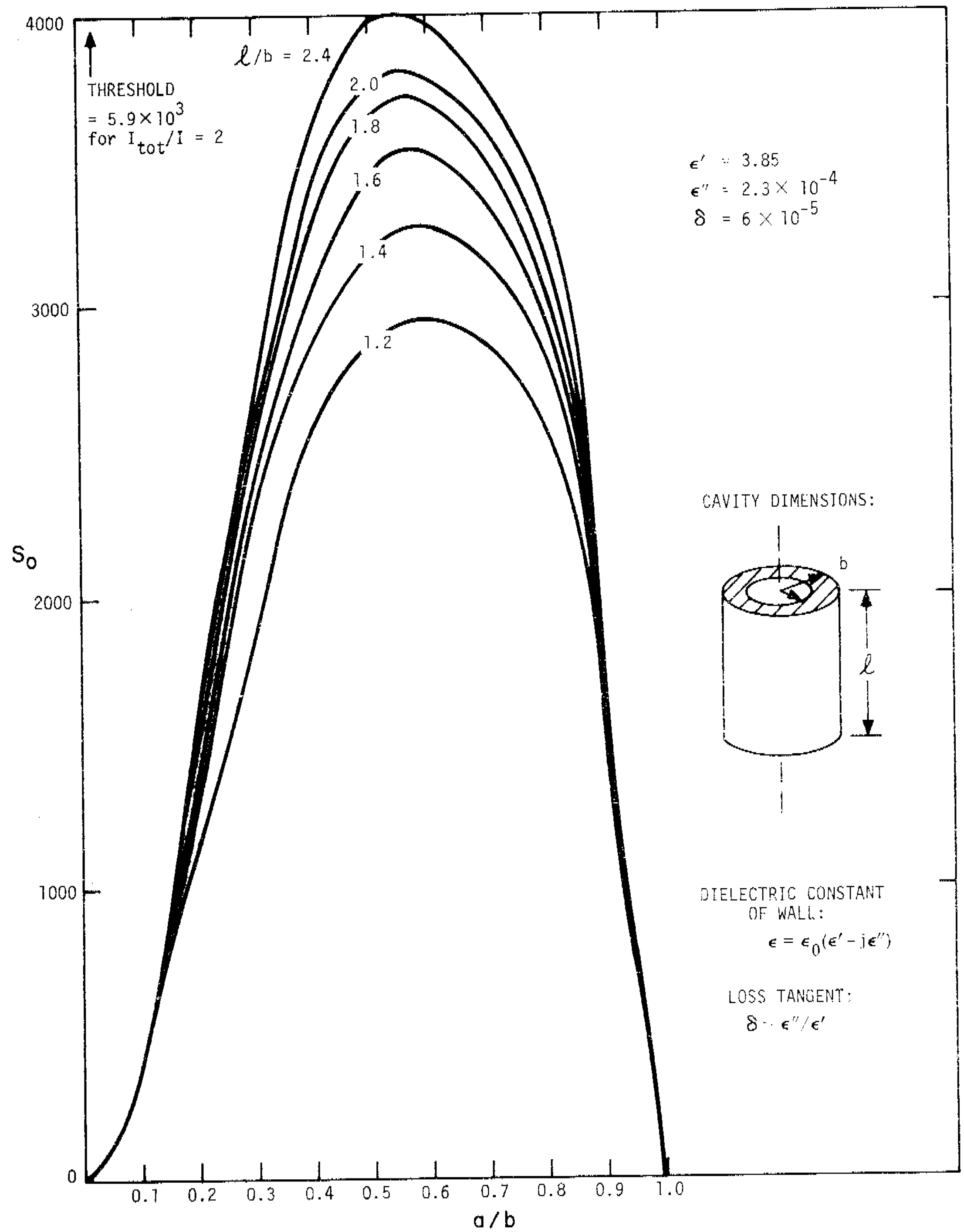

Fig. 4 S_O for Cylindrical Dielectric-Loaded Maser Cavity ideal silver coating, the cavity would require $\delta \leq 1.2 \times 10^{-5}$, well below the loss tangent of currently available fused silica.[6,7]

It is unlikely, therefore, that a material could be found that would allow a cylindrical loaded cavity to support maser oscillation.

Spherical Cavity

S_o for the spherical TE_{101} dielectric-loaded maser cavity is shown in Fig. 5 as a function of cavity radius for three values of loss tangent. If $\delta = 3.25 \times 10^{-5}$, S_o for a silver-coated cavity 19 cm in diameter satisfies the oscillation criterion. However, a maser with $\beta > 0$ and $Q < Q_{theor}$ will not oscillate. Such a spherical maser cavity, with a = 6.4 cm, b = 9.83 cm, has been built.[2] It has not operated successfully as an active oscillator, although it has been used in a maser with external gain to enhance the Q.[9] We have measured the cavity's unloaded Q and calculated its filling factor, obtaining $Q_o = 17.2 \times 10^3$ and $\eta' = 0.3450$. These values give $S_o = 5.92 \times 10^3$, barely above threshold for an isolated cavity. (From these data we deduce that the loss tangent of the quartz is $\delta = 3.1 \times 10^{-5}$.) Assuming $\beta = 0.1$ and $Q = 0.7_{theor}$, we find that $\delta \leq 1.0 \times 10^{-5}$ for oscillation, a factor of three less than the actual loss tangent. (If the coupling factor increases to $\beta = 0.15$ and and the cavity Q decreases to $Q = 0.6\ Q_{theor}$, Eq. 5 cannot be satisfied for any value of δ.)

We conclude that practical dielectric-loaded maser cavities cannot be made using currently available materials and conventional state selectors.

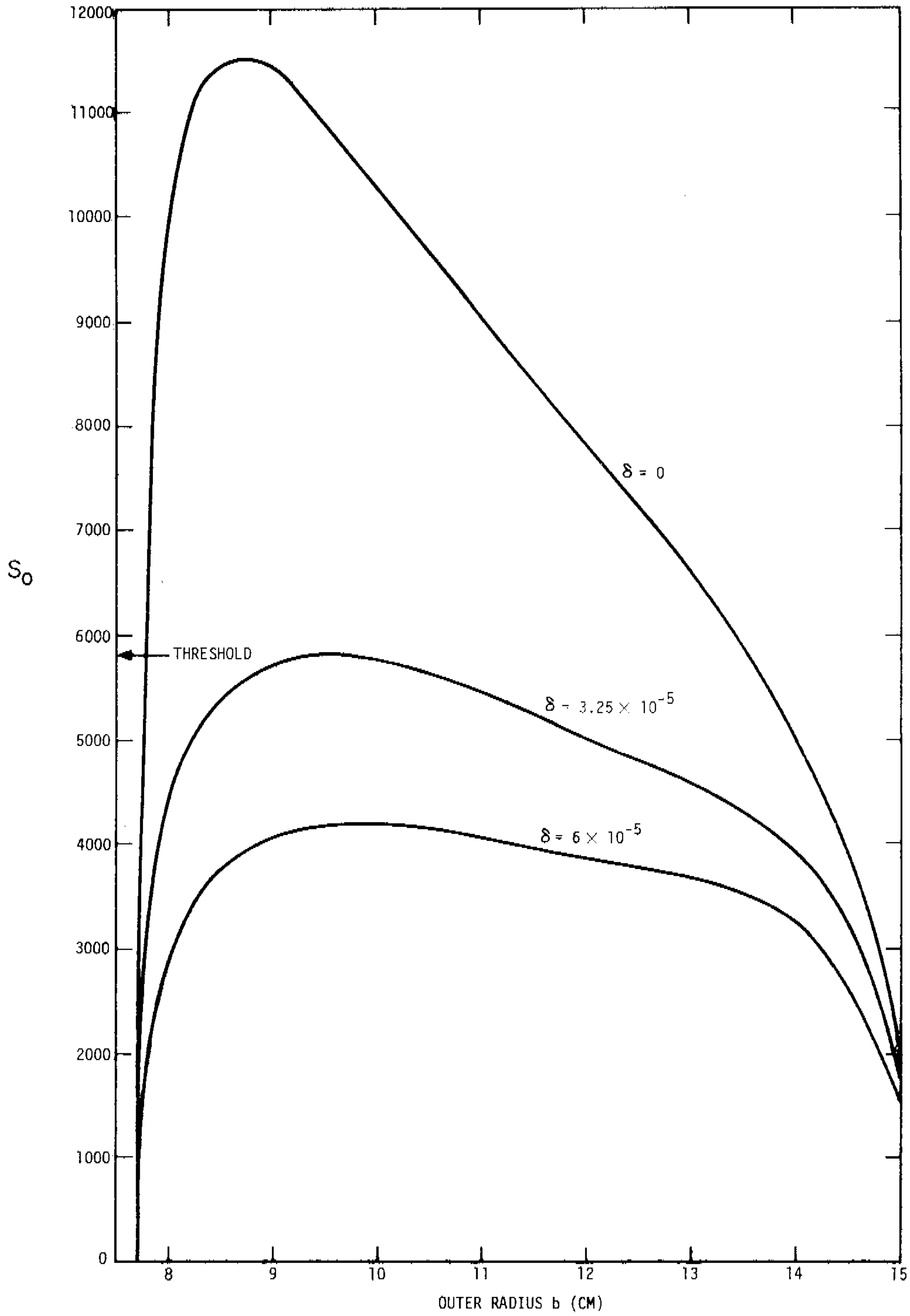

Fig. 5 S_O for Spherical Dielectric-Loaded Maser Cavity

IV Septum Cavities

Rectangular Septum Cavity

The dimensions of a rectangular TE_{101} cavity resonant at f_{hfs} are shown in Fig. 6. S_o for this cavity is given in Fig. 7 as a function of cavity shape. Because the fields in this resonator are independent of the y coordinate, Q_o and S_o increase with b. The filling factor η' improves as the cavity is made thinner (that is, as a/d decreases), but as shown in Fig. 6, d increases rapidly as a becomes smaller. A cavity approximately 19 x 19 x 13 cm (d/a = 0.7, b/d = 1) has $S_o = 13 \times 10^3$, and is expected to support oscillation. Its relatively large size (23 cm diagonal), however, is comparable with that of traditional cavities, while its rectangular shape makes difficult the production of a d.c. magnetic field that is uniform throughout its volume.

Cylindrical Septum Cavity

S_o for the cylindrical TE_{111} septum cavity is shown in Fig. 8. A convenient cavity size from the standpoint of efficient use of space and mimimum surafce-to-volume ratio is $\ell/D \sim 1$. S_o for a cavity with $\ell/D = 1.25$ is 13.2×10^3. With $\beta = 0.2$ and $Q = 0.7\ Q_{theor}$, this gives $S_{actual} = 7.7 \times 10^3$, 23% above the threshold value.

Fig. 9 is a photograph of a prototype septum cavity now being completed. For convenience of construction it is made of copper rather than low-expansion ceramic or glass. The rf output loop and the diode tuning loop will be covered with Teflon-coated quartz hoods, and the entire inner surface of the cavity will be coated with Teflon. The two halves will clamp the Teflon septum in place.

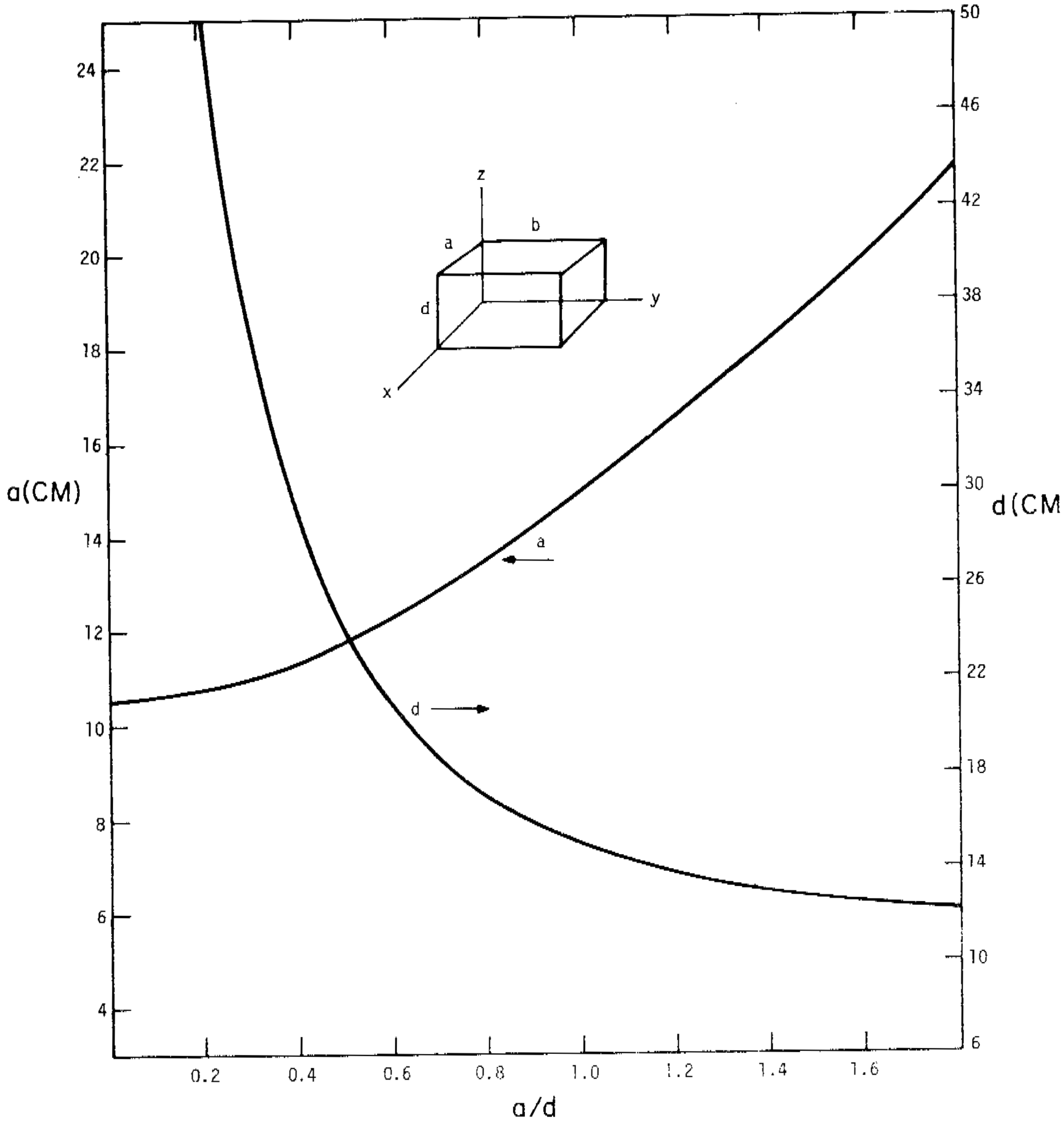

Fig. 6 Dimensions of TE_{101} Rectangular Septum Maser Cavity

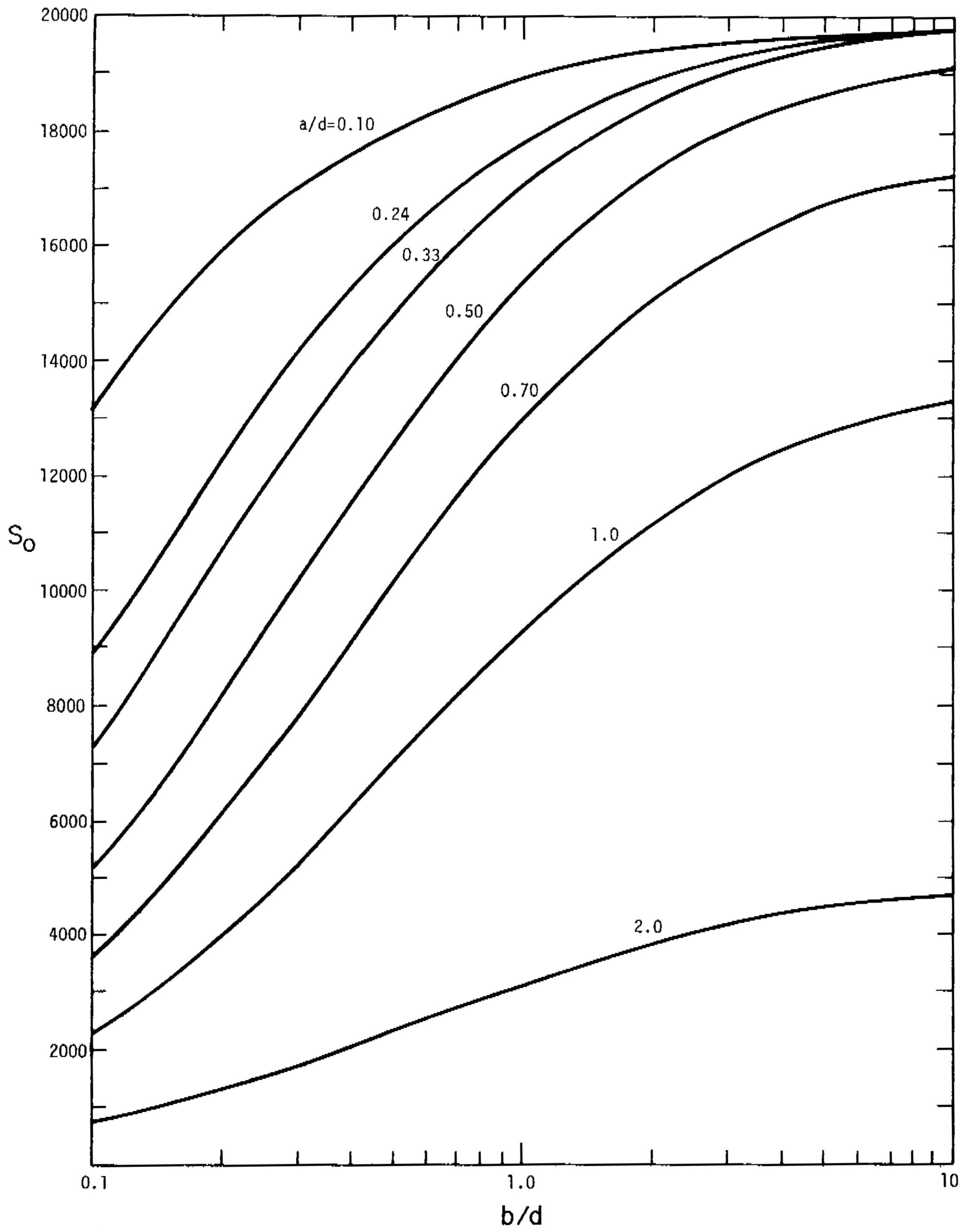

Fig. 7 S_O for TE101 Rectangular Septum Maser Cavity

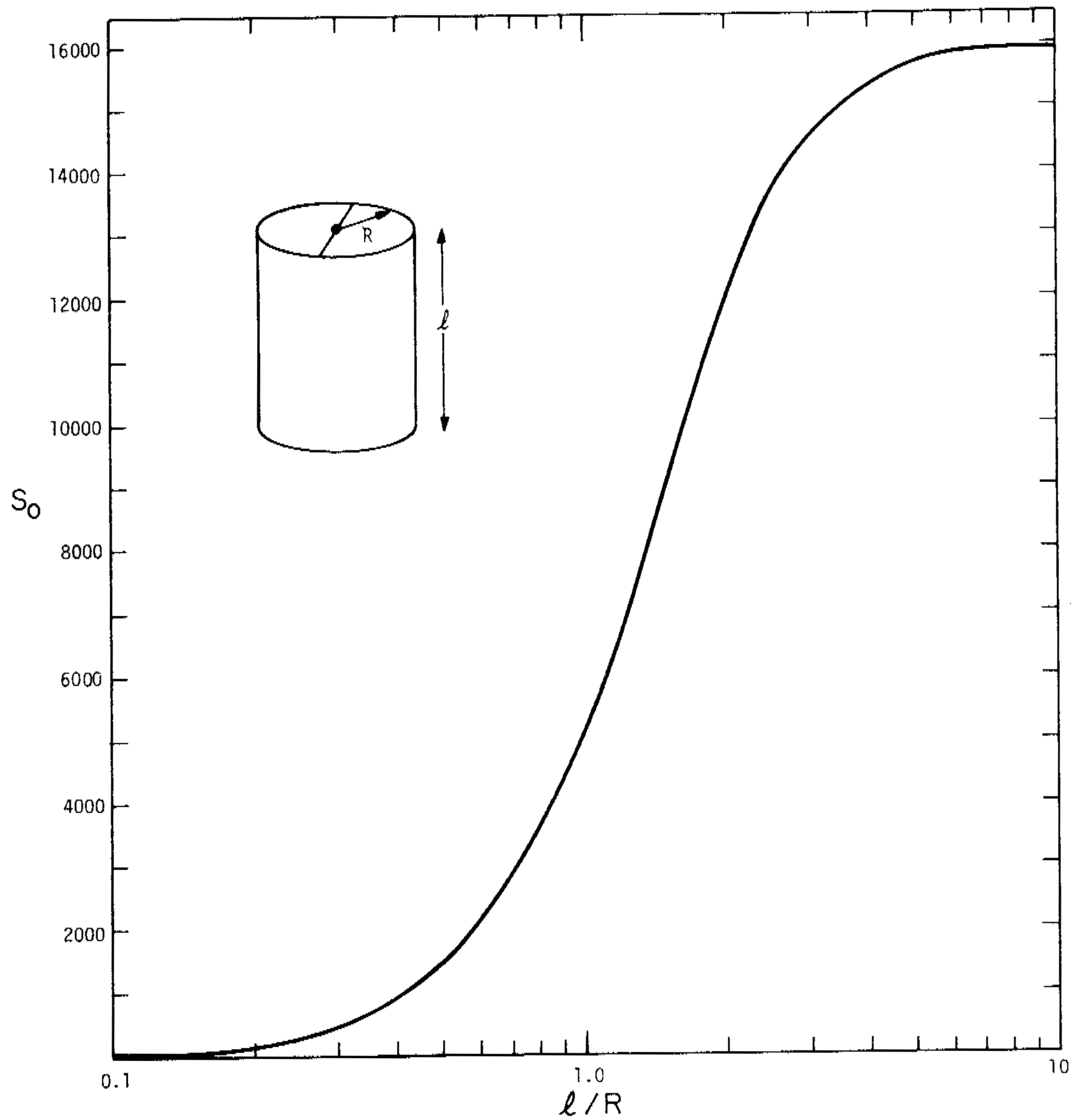

Fig. 8 S_o for TE_{111} Cylindrical Septum Maser Cavity

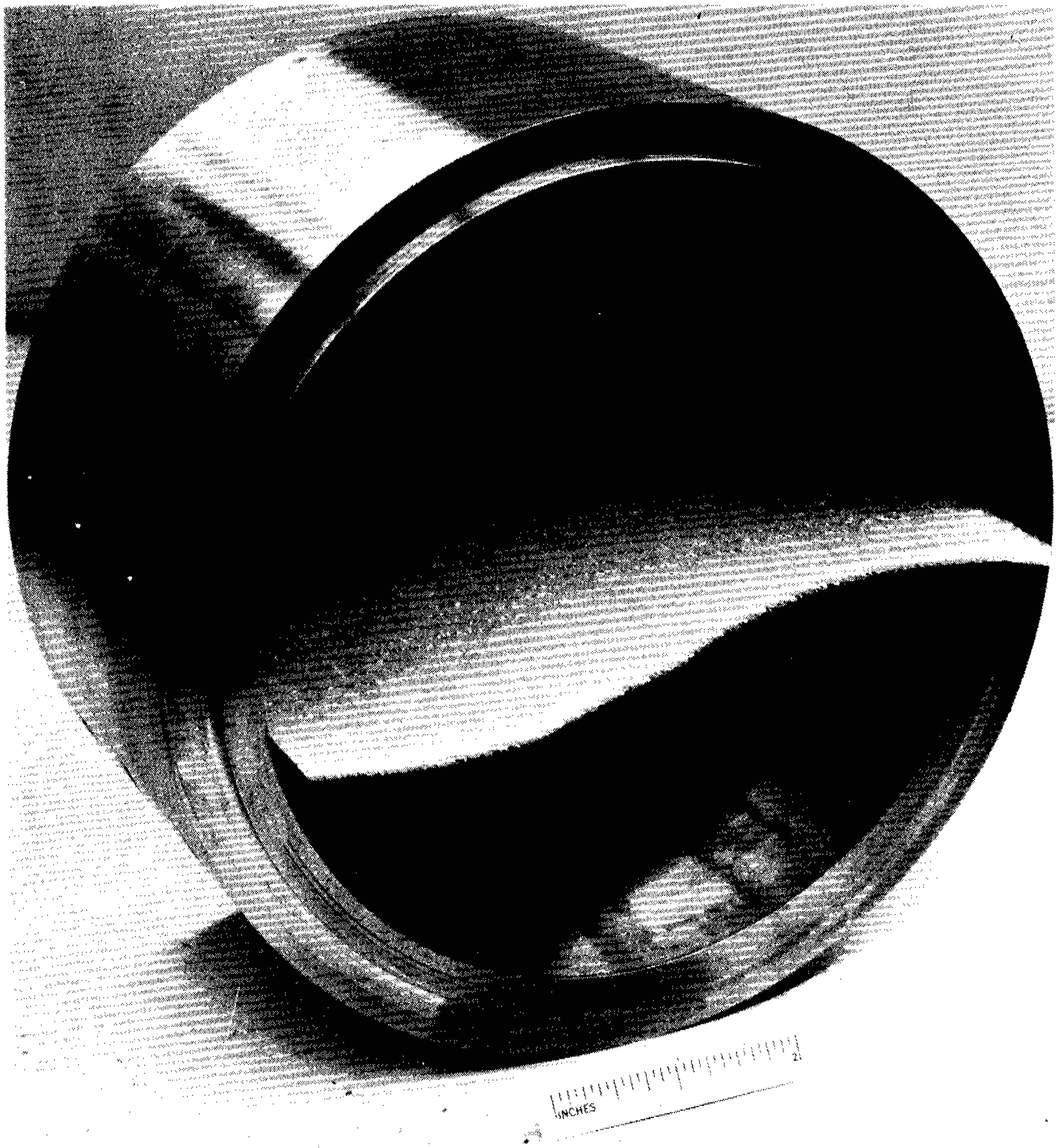

Fig. 9 Test Model of Cylindrical Septum Maser Cavity

V Maser for Space Applications

A conceptual design of a space maser is shown in Fig. 10. It is based on a cylindrical TE_{111} septum resonator, and uses cylindrical magnetic shields with rounded endcaps. We have measured the shielding factor $S_m = \frac{\Delta H\ ext}{\Delta H\ int}$ of such a shield, made of .036 cm (.014 inches) molypermalloy and found that S_m axial = 114, 37% greater than the axial shielding factor of a flat-ended shield of similar dimensions. The hydrogen source is a canister of lithium-aluminum hydride ($LiAlH_4$) whose output is regulated and purified by a heated palladium-silver diaphragm. Spent hydrogen is removed by three sorption pumps, while any residual gases are trapped by a small ion pump. Photodetectors monitor the light emitted by hydrogen atoms and molecules in the r.f. source discharge, permitting remote measurement of conditions in the discharge. (Many of these techniques have been developed for existing probe-rocket masers.) Power consumption is estimated at less than 25 watts. The maser is 58 cm (23 inches) long and 32 cm (12.5 inches) in diameter, with an estimated weight of 23 kg (50 lb).

Acknowledgement

We have recently learned from V. Reinhardt of independent work on a septum cavity by H. Peters and associates at Goddard Space Flight Center.

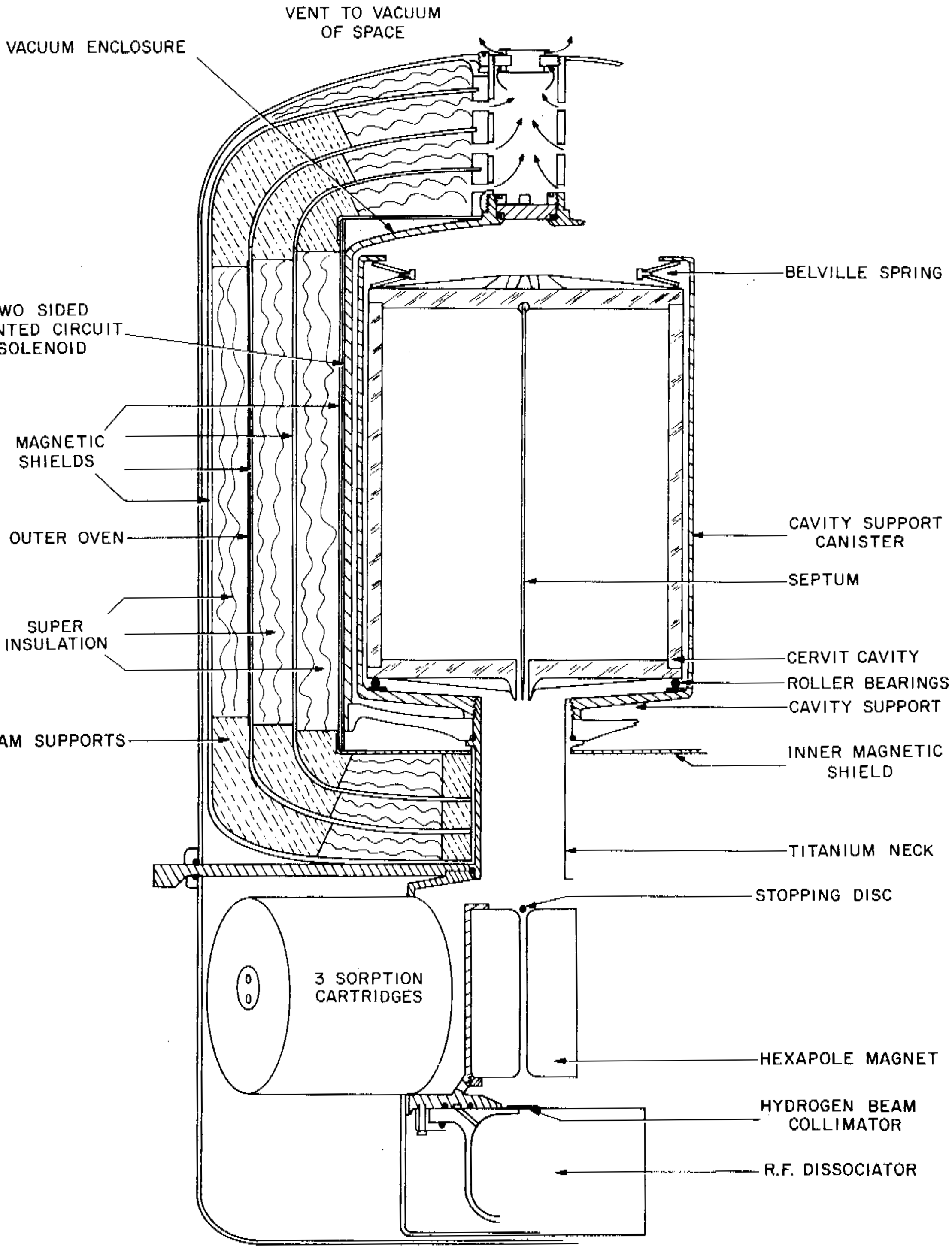

Fig. 10 Conceptual Design of Maser for Space Applications, Using TE_{111} Cylindrical Septum Cavity

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QUESTION AND ANSWER PERIOD

DR. REDER:

Dr. Reder, Fort Monmouth.

Wouldn't the septum introduce vibration sensitivity?

DR. MATTISON:

I don't believe it should. It would vibrate to a small extent, but it wouldn't change the frequency of the cavity to any great extent.

DR. REDER:

I must say the progress in this field is tremendous. Two years ago we talked about a walk-in maser.

MR. WARD:

Sam Ward, Jet Propulsion Lab.

What function do those roller bearings have?

DR. MATTISON:

Oh, that is also a means of isolating the cavity from any motion of the base support. In other words, the base can flex and those rollers take up any motion without causing flexure of the cavity base plate itself which would change the frequency of the cavity.