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A TUNER USING TRANSVERSELY BIASED MICROWAVE FERRITE FOR THE 114 MHZ PS CAVITIES

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S U M M A R Y

In order to displace the beam ± 10 mm radially, the 114 MHz PS cavities will be equipped with a fast tuning system. It consists of a transversely biased microwave ferrite tuner producing a 20 kHz frequency range. The losses are less than 500 W for 15 kW in the cavity.

This paper gives the microwave ferrite characteristics as well as the calculated and measured performance of the tuner.

1. INTRODUCTION

The 114 MHz cavities installed in the PS for e^- and e^+ acceleration [1] require a fast tuning system (20 kHz in 20 ms) to displace the beam $\pm$ 10 mm radially. For this purpose, a ferrite tuner has been developed.

Measurements done at Los Alamos [2] showed that microwave ferrites, biased perpendicularly to the RF magnetic field, exhibit Q factors higher than 1000 close to saturation; Q factors of classical ferrites, biased parallel to the RF field, are one order of magnitude lower.

To maintain the power losses at acceptable limits for our high Q cavities (50000), use of microwave ferrite perpendicularly biased has been investigated. From the characteristics (μ and Q) measured on microwave ferrite samples at signal level [3], a tuner optimized for low power loss has been designed.

2. CHARACTERISTICS OF THE SELECTED FERRITE AND ESTIMATION OF THE POWER LOSSES

Different types of ferrite samples have been measured, at signal level, in a test resonator [3]. The selected material is the GARNETS G810 from TRANS-TECH, INC. Figure 1 gives its permeability, μ, and its magnetic quality factor, Qmf, versus B, the transversel biasing magnetic field (perpendicular to the RF field). These results show that Qmf is higher than 1000 in a μ range 1.5 to 3.2 and rapidly falls at higher μ.

From the characteristic Q(μ), we can estimate Pf, the total power losses in the ferrite corresponding to the required frequency shift, Δf_0, and the quantity of ferrite necessary to dissipate the power losses. If, for μ varying from μmin to μmax, the ferrite tuner can be considered as an inductance proportional to μ* and directly coupled to the cavity (ΔU_0, the change of cavity stored energy equal to ΔUf, the change of magnetic energy in the ferrite), we get the following relations:

$$\frac{\Delta U_0}{U_0} = \frac{\Delta Uf}{U_0} = \frac{1}{2}\frac{\Delta f_0}{f_0} \qquad (1)$$

$$Uf(\mu) = Uf(\mu min)\,\frac{\mu min}{\mu max} \qquad (2)$$

$$\Delta Uf = Uf(\mu min)\,[1- \frac{\mu min}{\mu max}] \qquad (3)$$

$$Pf(\mu) = \frac{2\pi f_0 Uf(\mu)}{Qmf(\mu)} \qquad (4)$$

From (1), (2), (3) and (4) we deduce:

$$Pf(\mu) = \frac{4\pi U_0 \Delta f_0}{Qmf(\mu)}\,\frac{\mu min\ \mu max}{\mu(\mu max-\mu min)} \qquad (5)$$

If we now introduce in (5) the numerical values:

tuning range, Δf_0 = 20 kHz
stored energy in the cavity, U_0 = 1.2 Joules (for Vcav = 500 kV)

and consider the high Q range of the ferrite where μ varies from 1.5 to 3.2, we get:

Pfmax = Pf (μmin) = 550 W,

which correspond, for the cavity, to a quite reasonable Q drop of 3 %.

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* that supposed its electrical length short as compared to λ/4 at 114.5 MHz

With 8 ferrite rings (♦int = 8 cm, ♦ext = 16 cm, thickness = 1 cm) the power density is 0.4 W/cm^3 or 0.2 W/cm^2 which seems adequate for forced air-cooling.

In this first approach, if the μ range of the ferrite is fixed, the total power loss, which does not depend on the quantity of ferrite, is directly proportional to the desired frequency shift and varies as μ^{-1}; the quantity of ferrite influences only the power density and the coupling factor necessary to get the desired tuning range. Los Alamos measurements [2] showed that it is only valid within certain limits: at high power density the Q of the ferrite may drop (a factor 2 at 1.5 W/cm^3). But in our case, with a power density of 0.4 W/cm^3 we remain far enough from this limit.

3. LUMPED ELEMENT MODEL FOR THE TUNER COUPLED TO THE CAVITY

Figure 2 gives a rough description of the tuner coupled to the cavity. It consists in a short-circuited two-section coaxial line, coupled to the cavity by a loop, through a ceramic window. The high impedance section of the line is partly filled with the ferrite rings. A coil wound around its outer conductor produces the transversal bias magnetic field. A laminated iron yoke closes the circuit for the magnetic flux.

If we assume that, with the chosen dimensions, the following conditions are correct:

- the electric energy is concentrated in the ceramic window and in the low impedance section and does not depend on μ,
- the magnetic energy is concentrated in the high impedance section*,
- the high impedance section is completely filled with ferrite,
- the whole power loss comes from the magnetic losses in the ferrite,

the tuner can be modeled by the equivalent lumped circuit of Figure 3. Ls represents the self-inductance of the loop, Cp, the global capacitance

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* that supposed is electrical length short as compared to $\lambda/4$ at 114.5 MHz

(ceramic window, low impedance section, ...), Lf(μ), the inductance of the high impedance section (proportional to μ), r(μ), the magnetic losses in the ferrite ($r(\mu) = \omega_0 Lf(\mu)/Qmf$) and Vt, the loop induced voltage depending on the coupling factor (loop area).

The case previously studied corresponds to the particular condition: Ls = 0 and Cp = 0 (ferrite directly coupled to the cavity). We will see that the presence of the coupling elements Ls and Cp may limit the useful μ range and therefore, the tuning range.

4. EFFECTS OF THE COUPLING ELEMENTS

At constant magnetic Q, the power losses are proportional to the stored energy in the ferrite and the cavity frequency shift is proportional to the change of reactive power in the tuner. If by varying μ, we approach the series resonance of the tuner equivalent circuit, the stored energy in the ferrite increases faster than the total reactive power, causing a dramatic increase of the power losses for the same tuning range. A more detailed study is developed in the Appendix. Figure 4a compares the calculated stored energy in the ferrite versus μ, for Cp = 70 pF, Lf = μx11.5 nH, and different values of Ls. Figure 4b gives the corresponding frequency variation; to maintain constant the total frequency change for the different Ls values, the coupling factor (or the induced voltage, Vt) has been adjusted. For Ls = 0, the variations of the cavity frequency and of the stored energy in the ferrite do not depend on the value of Cp, if this element can be considered as loss-free; it only modifies the initial reactive power in the tuner. If Ls is increased, the stored energy in the ferrite decreases at low μ but increases at high μ and it may become excessively large, limiting the useful μ range, if we approach the series resonance. There is a value of Ls which corresponds to a nearly constant stored energy in the ferrite; this would be the ideal condition for a ferrite with constant Q in this μ range.

The lumped circuit of Figure 3 permitted to point out the eventual limiting effect of the coupling elements (Ls, Cp), but as previously mentioned, this model is an approximation of the real conditions. To approach closer the reality, we exploited the results of calculations performed with the computer program SUPERFISH.

5. MODEL USING THE RESULTS OF SUPERFISH CALCULATIONS

With SUPERFISH we could calculate, for different ferrite μ, the electric and magnetic field distributions in the real structure (included the ferrite rings and the ceramic window) by adding a line of variable length adjusted to keep the resonant frequency at a constant value (114.5 MHz). The input geometry for SUPERFISH is described in Fig. 5. As SUPERFISH does not offer the facility to introduce lossy materials and to take into account the loop, we came back to a "lumped" circuit model whose elements are deduced from the computed field distributions. The equivalent circuit, with a constant loop inductance Ls and the other elements depending now on μ, is described in Fig. 6. Vt is the loop induced voltage; the inductance Lf(μ) and the capacitance Cf(μ) correspond to the magnetic and electric energy stored in the ferrite; Ll(μ) and Cl(μ) represent the remaining inductance and capacitance of the circuit; Rs(μ) and Rp(μ) which represent the magnetic and electric losses in the ferrite are given by:

$$Rs(\mu) = \frac{\omega_0 Lf(\mu)}{Qmf(\mu)}$$

$$Rp(\mu) = \frac{Qef}{\omega_0 Cf(\mu)}$$

where Qmf(μ) is the measured magnetic Q of the ferrite versus μ and Qef its electric Q from datasheet (5000). Ll(μ) is constant (9 nH), Cl(μ), Cf(μ) and Lf(μ) are given in Figs. 7 to 9. These results confirm that the electrical losses in the ferrite are small compared to the magnetic losses (less than 5 %).

6. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

Figure 10 compares the power losses versus the cavity frequency shift calculated by this method and the experimental values obtained by measuring the cavity Q drop at signal level and extrapolated to the nominal voltage (Vcav = 500 kV) for a 80 x 70 cm^2 (Ls = 80 nH) coupling loop. We can notice the good agreement between theoretical and experimental results. This loop, optimized for minimum self-inductance, produced nevertheless a series resonance in the useful μ range, limiting Δf to 7 kHz for a maximum power of 500 W. Several other loops have been tested, but this remains the best performance we could achieve: larger loops produced a series resonance at lower μ values, smaller loops a too low coupling factor. In order to improve these conditions, it is necessary to use a larger loop and move the series resonance out of the useful μ range, by other means.

7. COMPENSATION OF THE COUPLING ELEMENTS

The value of Cl(μ) being practically imposed by our choice of a standard ceramic window and the mechanical constraints for its connection to the ferrite housing, Ls, by the required loop area, we decided to limit the apparent inductance by compensating it with a series capacitance. In practice, this could be realized by separating the loop into two branches, the gap between them behaving as a capacitance (Fig. 11).

Figure 12 compares the theoretical case where Ls $\simeq$ 0 and the experimental results obtained with this compensated loop. Again, a good agreement is found between measured and calculated values. This improvement permitted to reach a total frequency shift of 23 kHz and power losses lower than 500 W. With such a loop the induced voltage is 6 kV and the maximum voltage on the capacitance 7 kV; these conditions are quite acceptable for the chosen dimensions.

8. HIGH POWER TESTS

The measurement of the cavity Q drop at signal level permitted to evaluate the total power dissipated in the ferrite and then the average power density. A non uniform power distribution may locally enhance the power density. The computed field distributions indicated the following points:

- the contribution from the electric field in the ferrite is unimportant;
- the axial variation of the magnetic power density in the ferrite is lower than 15 %;
- radially, the power density at the inner diameter is two times higher than at the outer diameter*.

Power tests with DC biasing have been performed on a prototype similar to the tuner final version described in Fig. 13. Up to a power of 8 kW CW, without forced air-cooling, we did not encounter any problems of abnormal Q drop run away or local heating. In these conditions, we simulated an accidental fall of the ferrite polarization by switching off the current supply of the tuner coil. The consequences were a sudden detuning of the cavity, slowly compensated by the piston tuner and a resistive loading. In absence of an AVC loop, due to the resulting mismatch, the gap voltage dropped and no excessive power heated the ferrite. Complementary tests with the AVC loop are necessary to see if the cavity to amplifier mismatch is in itself sufficient to limit the power dissipated in the ferrite; otherwise the maximum delivered power would have to be limited by using a signal from the reflected power.

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* It is important to bias the ferrite uniformly by guiding the magnetic flux; a previous test run without iron yoke showed reduced performance in tuning range (factor 2).

CONCLUSIONS

With a compensation of the coupling loop inductance, the required tuning range of 20 kHz and power losses in the ferrite lower than 500 W could be achieved. Power tests up to 8 kW, CW, did not show up any difficulties. The eventual use of the tuner as an efficient damper for the parasitic modes excited by the beam - specially the fundamental mode during the proton cycles - will be investigated later.

ACKNOWLEDGEMENTS

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REFERENCES

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2. W.R. Smythe, T.G. Brophy, R.D. Carlini, C.C. Friedrichs, D.L. Grisham, G. Spalek and L.C. Wilkerson, "RF cavities with transversely biased ferrite tuning", Particle Accelerator Conference, Vancouver, May 1985.

3. R. Hohbach et al., "A ferrite tuner for the 114 MHz cavity", PS/RF/NOTE 85-3.

A P P E N D I X

LIMITING EFFECT OF THE COUPLING ELEMENTS ON THE TUNING RANGE

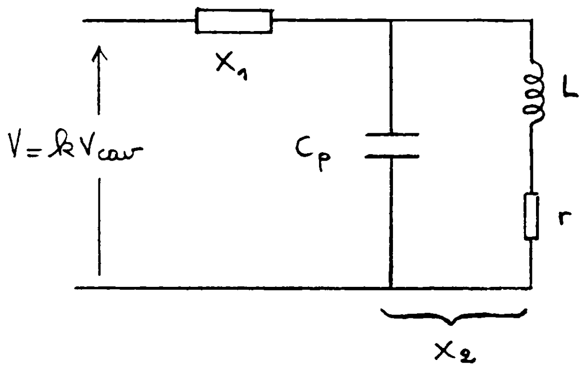

Figure 1A
Equivalent circuit for the ferrite tuner coupled to the cavity

Let us consider that the tuner coupled to the cavity can be modeled by the lumped circuit described above with the following definitions:

V : the coupling loop induced voltage proportional to the cavity gap voltage (k: coupling factor depending on the loop area);

x_1 : the coupling loop reactance (in general x_1 = Ls, the loop self-inductance);

L : the ferrite equivalent inductance proportional to μ its relative permeability ($L = \mu L_0$, $Li = \mu min\ L_0$, $Lf = \mu max\ L_0$);

Cp: the remaining reactance (supposed capacitive) of the tuner;

r : a resistance representing the magnetic losses in the ferrite ($r = \omega_0 L/Qmf$; Qmf is the ferrite magnetic Q, $f_0 = \omega_0/2\pi$, the cavity resonance frequency);

$$x_2 = \left(\frac{1}{\omega_0 L} - Cp\ \omega_0\right)^{-1}, \quad x_{2i} = x_2(\mu min), \quad x_{2f} = x_2(\mu max).$$

The cavity frequency shift Δf is proportional to ΔPr, the change of reactive power and, at constant Qmf, the power losses are proportional to Uf, the energy stored in the ferrite. For μ varying from μmin to μmax, we can write:

$$Pr = \frac{1}{2} V^2 \frac{1}{x_1+x_2} \tag{1}$$

$$Uf = \frac{1}{2} \frac{V^2}{\omega_0} \left(\frac{x_2}{x_1+x_2}\right)^2 \frac{1}{L\omega_0} \tag{2}$$

and

$$\Delta Pr = \frac{1}{2} V^2 \frac{x_{2f}-x_{2i}}{(x_{2i}+x_1)(x_{2f}+x_1)} \tag{3}$$

ΔPr is fixed by the required frequency change, Δf_0 and for different values of x_1, V (or the coupling factor) must be adjusted to keep it constant. If we suppose that $\Delta f = \Delta f_0$ for $x_1 = 0$ and $V = V_0$, we get in the general case ($x_1 \neq 0$):

$$V^2 = V_0{}^2 k_0$$

where

$$k_0 = \frac{(x_{2i}+x_1)(x_{2f}+x_1)}{x_{2f}-x_{2i}}$$

and, replacing V by its value in (2):

$$Uf = \left(\frac{x_2}{x_1+x_2}\right)^2 k_0 Uf_0 \tag{4}$$

where

$$Uf_0 = Uf(x_1 = 0) = \frac{1}{2} \frac{V_0{}^2}{\omega_0} \frac{1}{L\omega_0}$$

These results show that, for $x_1 = 0$, the capacitance Cp neither influences the power losses nor the frequency variations; it only modifies the initial reactive power in the tuner. But, for $x_1 \neq 0$, to achieve the required cavity frequency change in the fixed μ range, the coupling must be corrected by a factor depending on both Cp and x_1. In addition, the frequency variations and the power losses versus μ depend on these two elements. If, by varying μ, we approach the series resonance condition ($x_2 \simeq -x_1$), Uf, which varies as $(x_1+x_2)^{-2}$ increases faster than Pr which varies as $(x_1+x_2)^{-1}$; consequently, the power losses can become dramatically high for the same tuning range. In the general case, the series resonance may happen if x_1 is inductive and x_2 capacitive or inversely (x_1 is capacitive, for example, if Ls, the loop inductance is overcompensated with a series capacitance). Figure 2A compares the energy stored in the ferrite versus μ for different values of x_1: a) when x_2 is capacitive in the whole μ range, b) when x_2 is inductive in the whole μ range, c) when x_2 is inductive at low μ and capacitive at high μ. Figure 3A gives the corresponding cavity frequency variations; for each case the coupling factor (or the induced voltage), has been adjusted to keep the tuning range at a constant value (25 kHz). The results are summarized in Table A (some conditions of this theoretical study may not be realistic). Our particular set-up corresponds to the case a), where x_2 is always capacitive; without compensation of the loop inductance the conditions are close to (4) and with the compensated loop to (2).

a) $x_2 < 0$	x_1	$-\infty$	0	x_a	$\simeq -x_{2f}$	$-x_{2i} > x_1 > -x_{2f}$	$\simeq -x_{2i}$	$+\infty$
	curve	6	1	2	3	4	5	6
b) $x_2 > 0$	x_1	$-\infty$	$\simeq -x_{2f}$	$\simeq -x_{2i}$	0	x_c	$+\infty$	
	curve	3	4	5	1	2	3	
c) $x_2 > 0$ (low μ)	x_1	$-x_{2i}$	0	x_b	$-x_{2f}$			
$x_2 > 0$ (high μ)	curve	4	1	2	3			

TABLE A

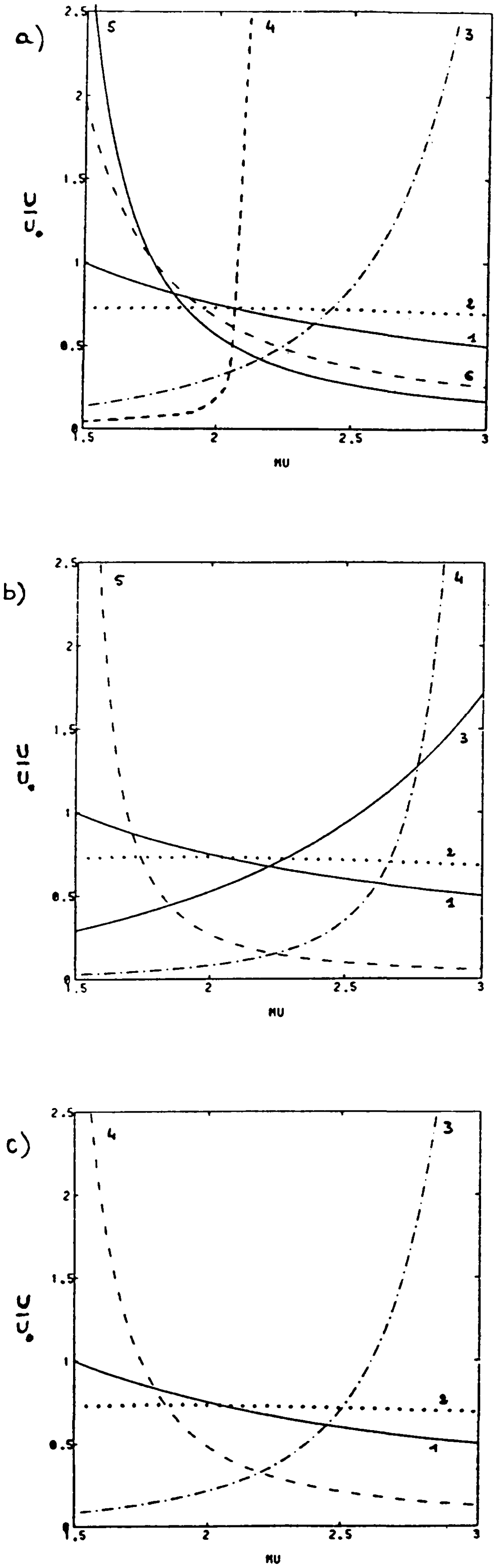

Fig. 2A: Normalized stored energy in the ferrite versus μ for different values of Ls

a) $x_2 < 0$

b) $x_2 > 0$

c) $x_2 > 0$ at low μ, $x_2 < 0$ at high μ

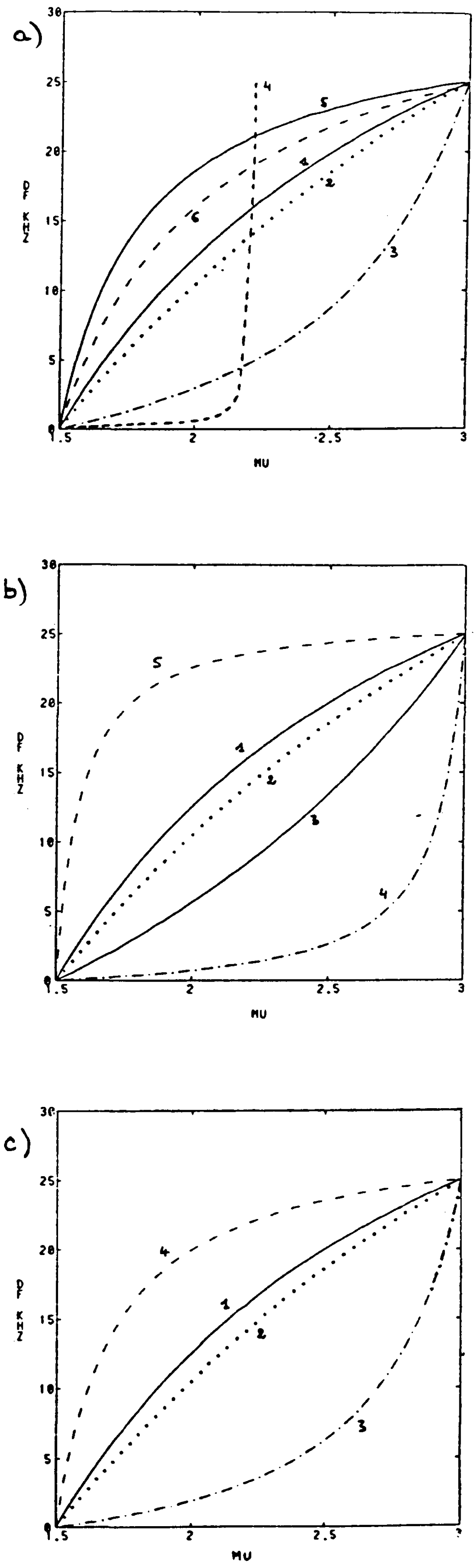

Fig. 3A: Cavity frequency shift versus μ for different values of Ls

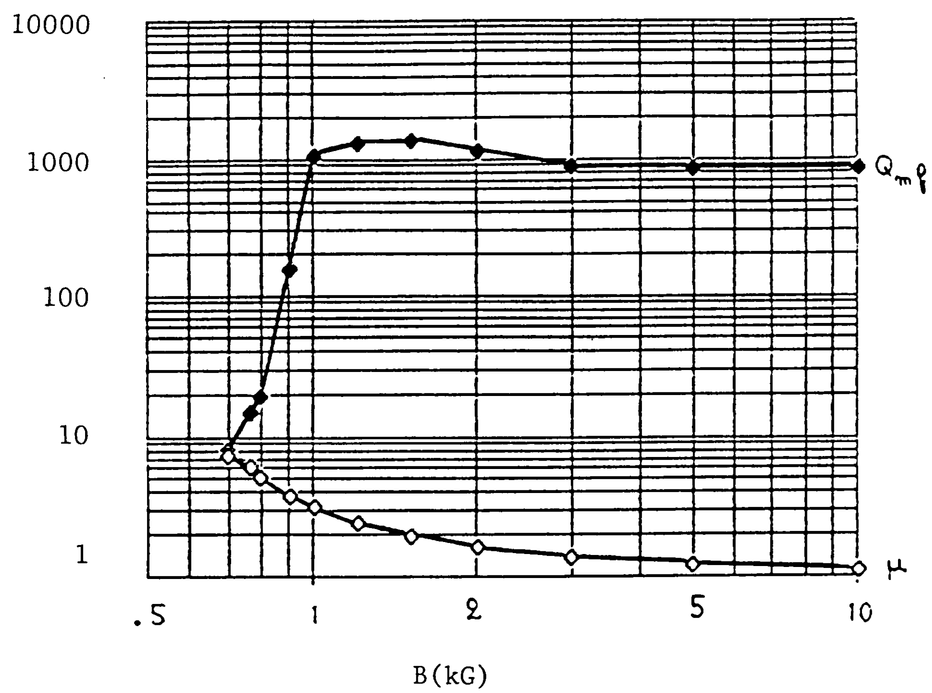

Figure 1

Measured magnetic quality factor and permeability of the microwave ferrite (GARNETS G810) versus the transversel bias magnetic field

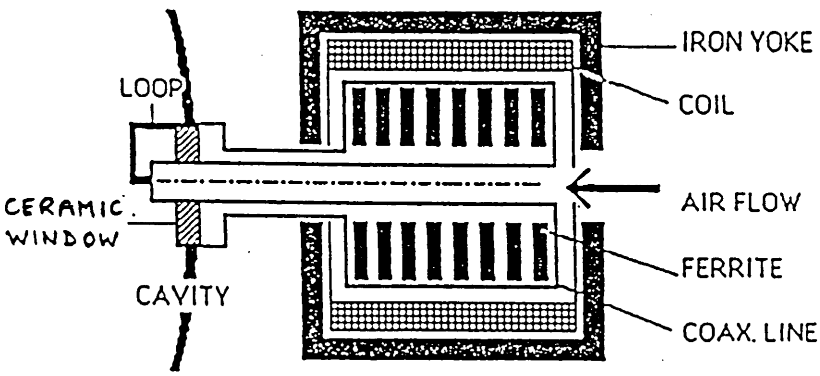

Figure 2

The ferrite tuner coupled to the cavity

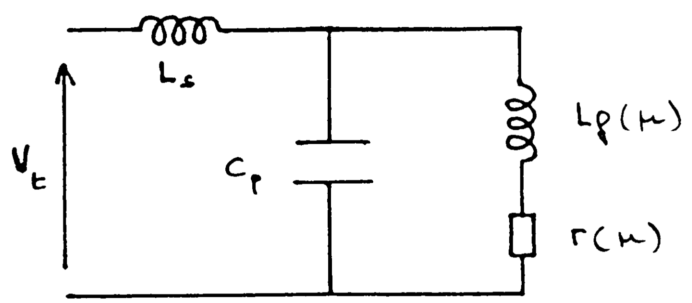

Figure 3

Equivalent circuit for the ferrite tuner

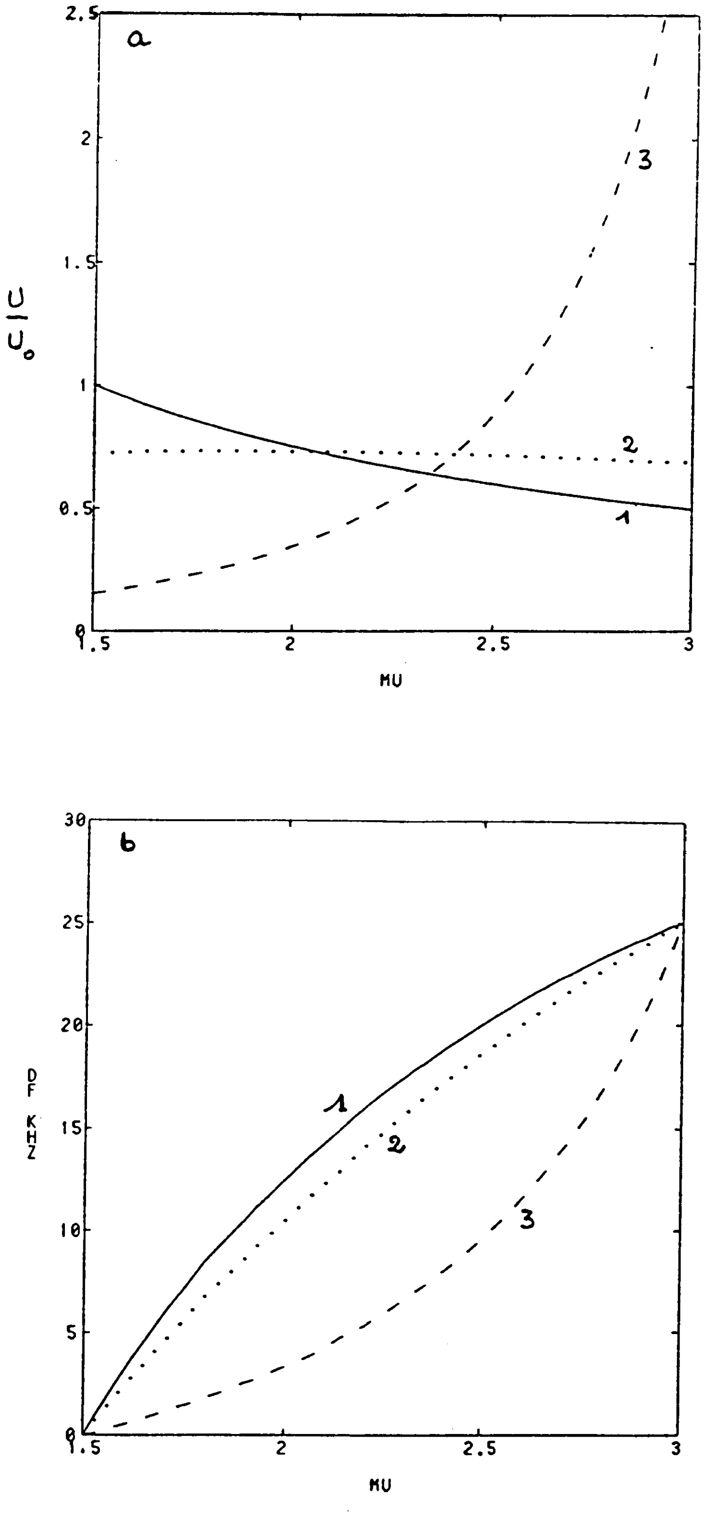

Figure 4

a) Normalized energy stored in the ferrite and b) cavity frequency shift versus μ, the ferrite relative permeability for different values of the loop self inductance ((1): Ls = 0, (2): Ls = 12 nH, (3): Ls = 78 nH) and Cp = 70 pF, Lf = μ* 11.5 nH.

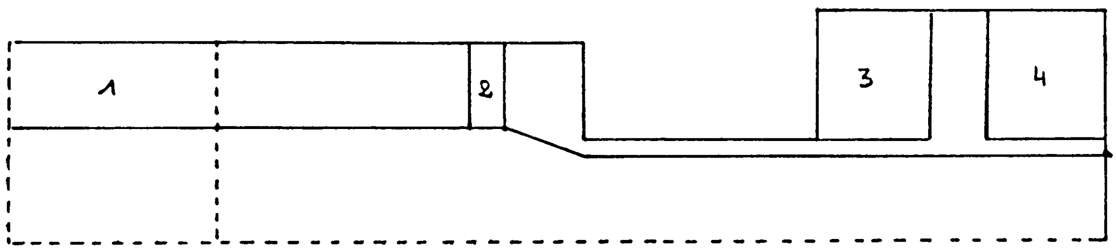

Figure 5

Input geometry for SUPERFISH
1: line of adjustable length
2: dielectric material of the window (ε = 10)
3,4: ferrite (ε = 14, variable μ)

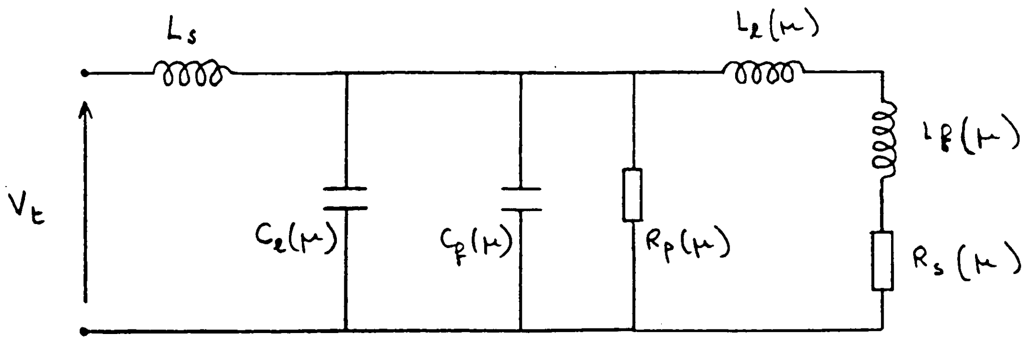

Figure 6

Tuner equivalent circuit
(elements calculated with SUPERFISH)

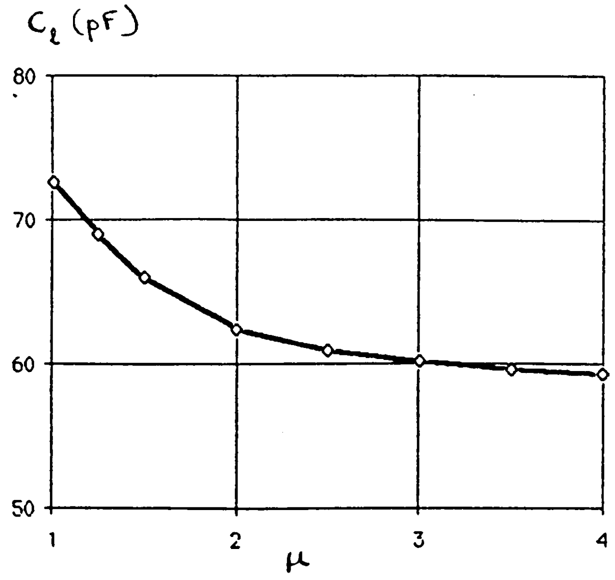

Figure 7

C_ℓ versus μ calculated with SUPERFISH

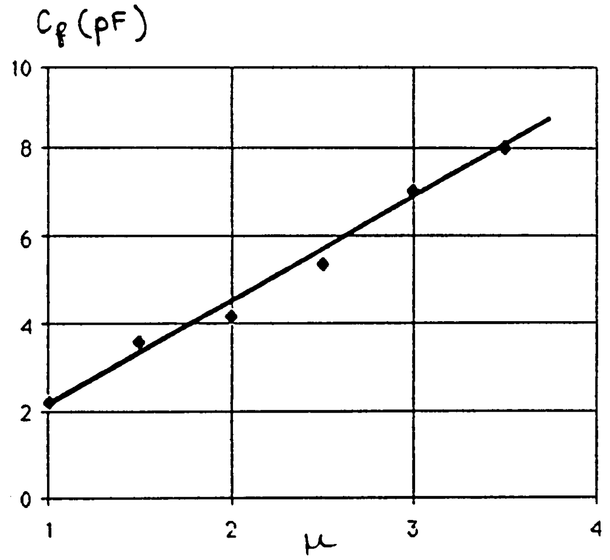

Figure 8

Cf versus μ calculated with SUPERFISH

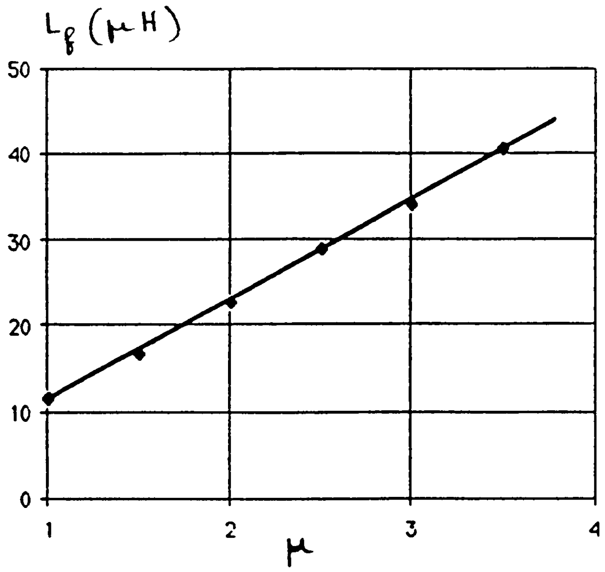

Figure 9

Lf versus μ calculated with SUPERFISH

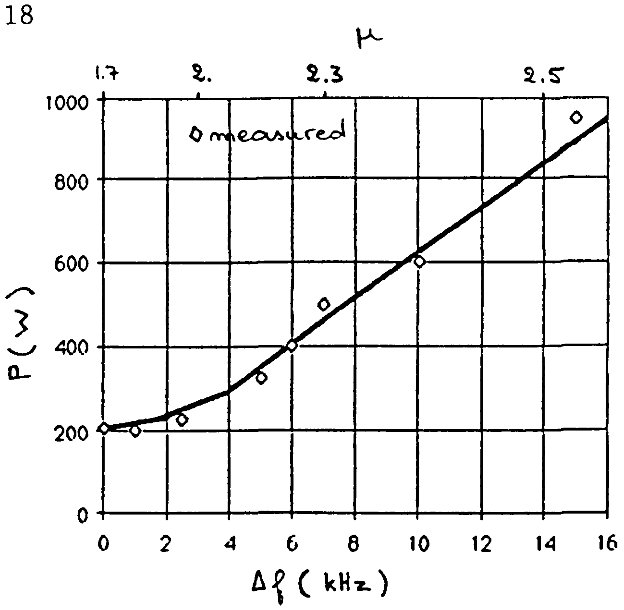

Figure 10

Calculated and measured power loss versus cavity frequency shift with a 80x70 cm^2 (Ls = 80 nH) coupling loop

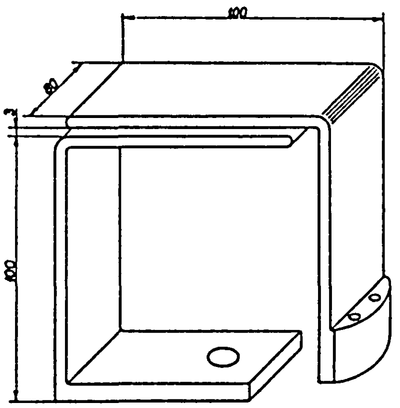

Figure 11

The compensated coupling loop

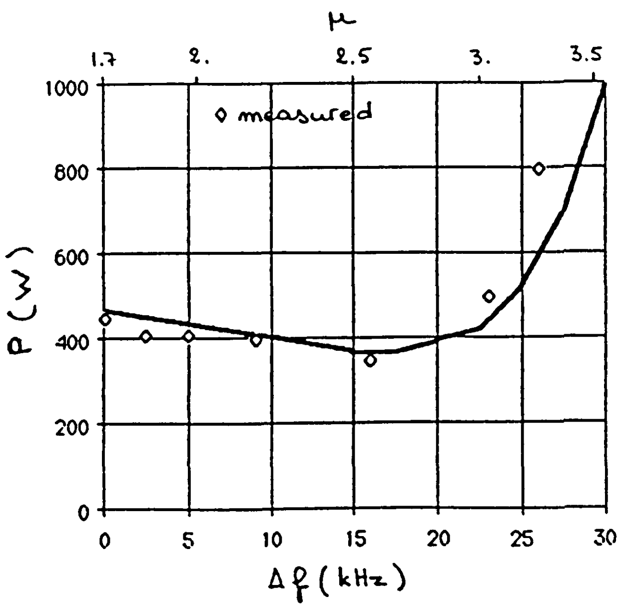

Figure 12

Calculated and measured power loss versus cavity frequency shift with the compensated coupling loop

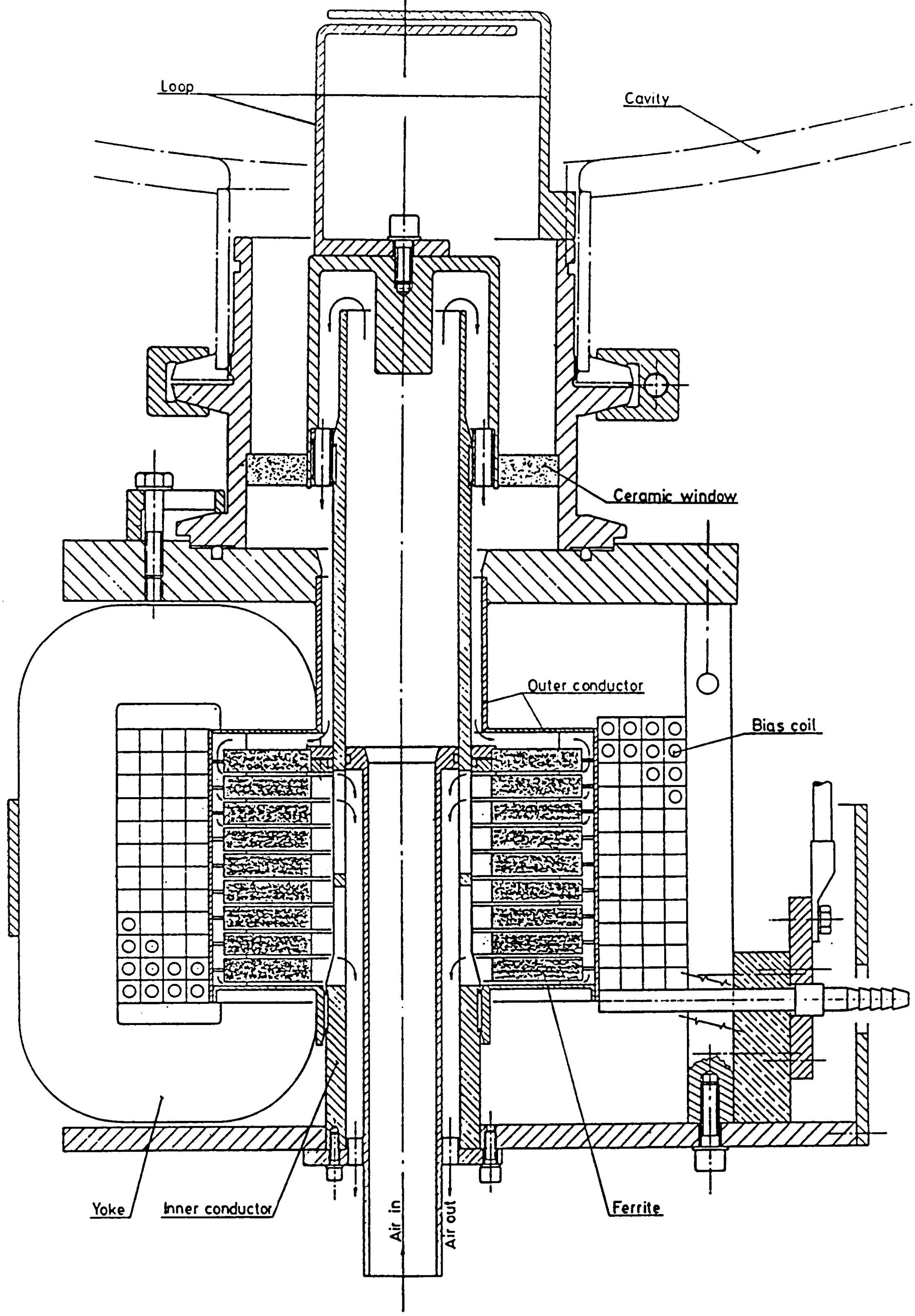

Figure 13

Mechanical drawing of the tuner final version