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A Study of Ferrite Cavity

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A STUDY OF FERRITE CAVITY

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Abstract. This note addresses the general concerns for the design of a ferrite cavity. The parameters are specified for the RCMS, for which the frequency ramp is in the range of 1.27 MHz to 6.44 MHz, or a ratio of 1:5.

INTRODUCTION

A challenge of the RCMS RF is its requirement for a wide range of frequency ramp with a repetition rate of 30 Hz, namely from 1.27 MHz to 6.44 MHz, or a ratio of 1:5. In the beginning non-tuning options were studied in considering the required voltage is quite modest. However, the study shows that the power source needed to accommodate the reactive power is very large and thus causes the cost to be unacceptable.[1-3]

It is then considered that ferrite tuning may be good and economic. At first, the ferrite tuning was rejected in considering the fact that it has inertial of its permeability.[1] It is thought that a rate of 30 Hz may be just at the margin. There are two possibilities to overcome this worry.

(1) Since the scan speed is known and fixed, one can test the delay time in advance. Correspondingly, the biasing current may be also in an advanced phase so as to compensate the delay.

(2) As has been studied, the serious problem is on those points that the frequencies are far from the resonance. Once the ferrite is biased for tuning, although it may not set perfectly on resonance due to inertial or so, but it will close to resonance anyhow, and will significantly reduce the required drive power.

Since the study of RCMS has gone through several iterations, the RF parameters had to be changed correspondingly. Table 1 listed some general specifications in different scenarios.

Table 1

Parameter	Unit	Case I	Case II	Case III
Circumference	m	24.2	28.6	28.6
Beam energy, inj	MeV	7	7	7
Beam energy, ext. (max)	MeV	250	250	250
Repetition rate	Hz	30	30	30
Revolution Freq. inj.	MHz	1.505	1.273	1.273
Revolution Freq. ext.	MHz	7.602	6.432	6.432
Gap voltage (max)	kV	7.0	6.5	8.0
Stable phase (max)	deg	41.9	57	
Number of cavity		1-2	2	1
Effective length of cavity	cm	85	85	131

As far as RF is concerned, the most important parameters are the voltage and frequency ramp. In regard to a safe leeway, the maximum gap voltage is desired to be 8 kV rather than 6.5 kV as shown in the last column.[4] The frequency and voltage ramp curves of the final case are shown in Fig.1. The response of voltage with frequency is shown in Fig.2.

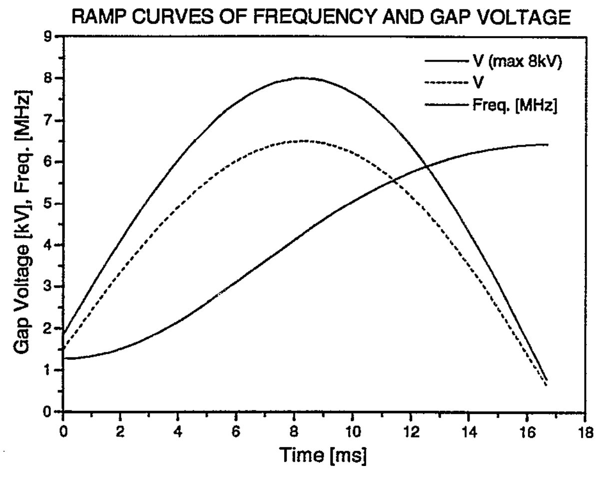

Fig.1 Frequency and voltage ramping curves

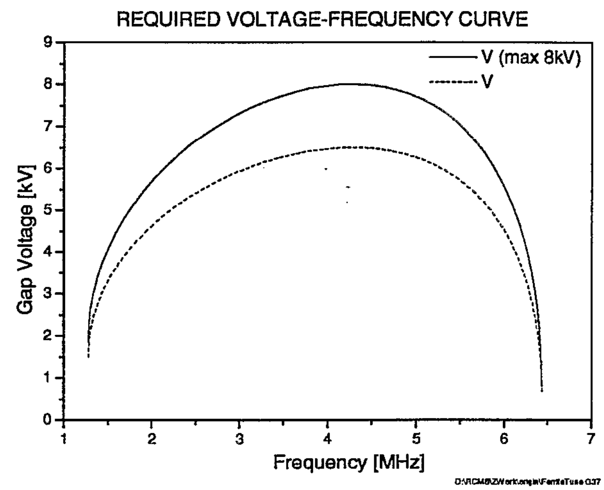

Fig.2 Gap voltage vs frequency

The ferrite material and size were also considered with different options. Table 2 lists what has been studied.

Table 2 Ferrite parameters

	Case 1		Case 2	Case 3
Material	4M2	4L2	4L2	4L2
Number of rings	14-21		14	?
Outer diameter	50 cm		50 cm	50 cm
Inner Diameter	12.5-25 cm		18 cm	18 cm
Thickness	2.7cm		2.7cm	2.7cm

A COMPARISON BETWEEN TUNING AND NON-TUNING

The equivalent circuit of a simple cavity with ferrite tuning is shown in Fig.3. The gap voltage is specified in the lattice design. The driven current *Is*, however, is determined by the tuning status as shown in the following expression.

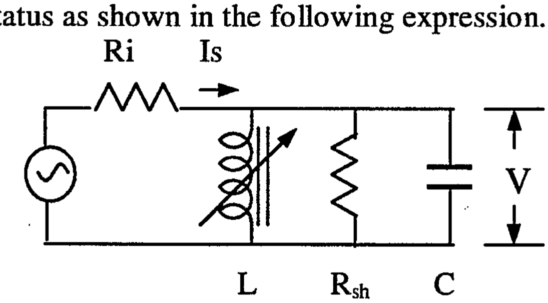

Fig.3 The equivalent circuit of a simple cavity

$$\frac{I_s}{V}=\frac{1}{R_{sh}}+j\left(\omega C-\frac{1}{\omega L}\right)=\frac{1}{R_{sh}}\left[1+jQ\left(\frac{f}{f_0}-\frac{f_0}{f}\right)\right] \qquad (1)$$

where $Q = R_{sh}/\omega_0 L$, $\omega_0^2 = 1/LC$, $f = \omega/2\pi$ and $f_0 = \omega_0/2\pi$. Obviously, I_s reaches its minimum at resonance, i.e. $f = f_0$. The quantity in the bracket in RHS is the current multiplication due to being off resonance.

Fig.4 and Table 3 show the results. As can be seen, the driver current increases rapidly when the frequency shifts away from the resonance. So does the power. The Q of the ferrite can be of the order of 100 to 200 or more. This means that even if it is off-resonance by only10%, the power required is 21 to 42 times larger than that for a perfect tuning.

If one puts on an extra load resistor to reduce the Q to 50, a 10% offset still requires a power 10 times larger than that of resonance. But, it should be noted that lowering Q can reduce only the frequency sensitivity; it can not reduce the power requirement, because it increases the power in the resonance also. This can be easily seen from Fig.3 and the expression (1).

Table 3 Current multiplication due to being off resonance

Freq. Off-resonance	Q = 50	Q = 100	Q = 200
5 %	5.2	10.3	20.6
10 %	10.6	21.1	42.2
20 %	22.5	45	90
A band of 1:5	91	183	367

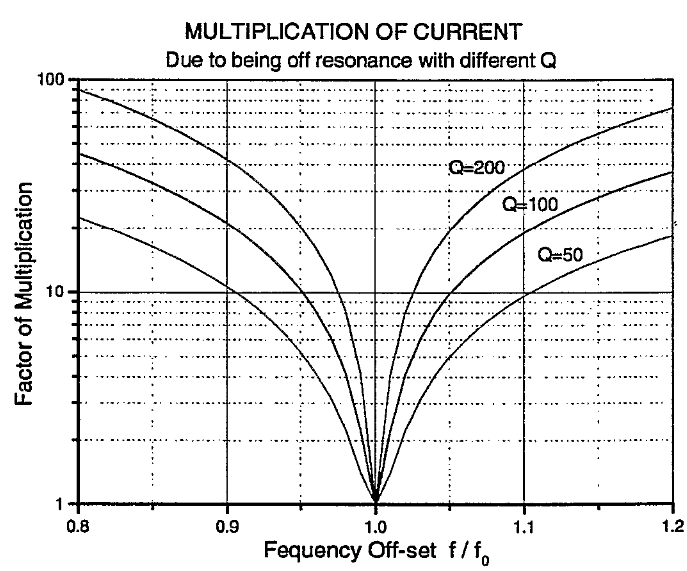

Fig. 4 Current multiplication due to being off resonance

This section emphasizes the importance of the resonance. One must carefully tune it as close to the resonance as possible when the biasing is applied. Detailed calculations indicate that a simple bias current, a current with sine waveform for example, is not good enough.[3] A more delicate biasing to approach resonance is necessary.

CAVITY AND INDUCTANCE

Unlike a microwave cavity, the cavity involving ferrite and operating in the MHz frequency range plays mainly the role of an inductance rather than a resonator. The capacitance shown in Fig.3 consists of two parts, i.e. an external capacitor and the stray capacitance. Inside the cavity is only stray capacitance. A lumped external capacitor is necessary. The inductance also consists of two parts, i.e. due to ferrite and strays. Since the inductance changes in a wide range in order to accommodate the tuning requirement, the stray part is not ignorable at the high frequency. We have to calculate both ingredients.

The inductance of ferrite

The flux in the air is ignored for the moment and at low frequency the current along the cavity axis can be regarded as constant. For a short coaxial line the inductance is:

$$L = l\frac{\mu}{2\pi}\ln\frac{r_2}{r_1} = N\,d\mu_0\frac{\mu_r}{2\pi}\ln\frac{r_2}{r_1} \tag{2}$$

where $l = Nd$ is the total length of ferrite, N the number of ferrite rings and d the thickness of each ring, r_1 and r_2 the inner and external radius of ring respectively. Substituting the parameters of Case 2 in Table 2, and $\mu_r = 200$ results in $L = 15.5\ \mu H$.

The stray inductance

The stray inductance in the cavity consists of two parts: (1) The flux in the space where the cavity is not filled by ferrite. (2) The stray inductance of the connecting wires. With the parameters of Case 2 in Table 1, the estimation is as follows.

(1) The inductance in a coaxial cavity filled with air is

$$L_{st} = l\cdot\frac{\mu_0}{2\pi}\ln\frac{r_2}{r_1}. \tag{2a}$$

The space not filled with ferrite can also be divided into two parts.

a) The space between the inner surface of the ferrite rings and the outer surface of the beam pipe. Assuming $r_2 = 9$ cm, $r_1 = 5$ cm, $l = 80$ cm, then $L_{sta} = 9.4\times10^{-8}\ H$.

b) The space of the gap between ferrite rings. Assuming $r_2 = 25$ cm, $r_1 = 9$ cm, $l = 80 - 14\times2.7$ cm $= 42$ cm, then $L_{stb} = 8.6\times10^{-8}\ H$.

The total stray inductance is 0.18 μH.

(2) The stray inductance due to the connector is complex and strongly depends on the real structure. In order to minimize the stray inductance, one should put the resonant capacitance as close to the acceleration gap as possible and use copper tapes as its connector. The inductance per unit length of copper tape pair is approximately

$$L_1 \approx \mu_0\frac{d}{w}, \quad \text{and total is} \quad L_{wire} = L_1 \times l \tag{3}$$

where d is the distance between the tape, and w the width of the tape, l the tape length between the capacitor and the surface of the acceleration gap. Assuming $d = w$, and that the capacitor is right outside the cavity, $l = 0.25$m (or 0.4m), then

$$L_{wire} = 0.32\ \mu H\ (0.5\ \mu H)$$

The total stray inductance is

$$L_{st} = 0.18 + 0.32\ \mu H\ (0.5\ \mu H) = 0.5\ \mu H\ (0.7\ \mu H)$$

To be conservative, a total stray inductance of $1\mu H$ would be a reasonable approximation. The following Table lists the related parameters.

Table 4

Bias field	A/m	0	3000
Relative Permeability		200	8
Inductance	μH	15.5	0.62
Stray inductance	μH	1	1
Total inductance	μH	16.5	1.62

Therefore, the tuning ratio is limited to be:

$$\frac{f_{\max}}{f_{\min}} = \sqrt{\frac{L_{\max}}{L_{\min}}} = \sqrt{\frac{16.5}{1.62}} = 3.19 \tag{4}$$

We conclude that one cavity is not able to cover a frequency range of 6.45 MHz to 1.273 MHz, or a ratio of 5 : 1.

RF POWER LOSS IN THE FERRITE

The ferrite is a non-linear dielectric, which makes it difficult for a precise numerical design. Nevertheless, a reasonable estimation is necessary and possible.

For the cavity, the resistance loss in copper is much less than the dielectric loss in ferrite and thus is ignored here. The loss in the ferrite is non-uniform in both space and time. There are 4 parameters of concern:

(a) The spatial average loss, which determines the real power delivered from the power source.
(b) The spatial maximum loss, which should be within a limit.
(c) The total time average loss, which determines the total heat needed to be removed by the coolant.
(d) The maximum time average loss, which checks for local overheating.

The power loss density in the ferrite is known to be

$$P_d = \frac{\pi}{\mu_0} \cdot \frac{B^2 f}{(\mu_r Q)} = \frac{2.5 \cdot 10^6 B^2 f}{(\mu_r Q)} \quad [\frac{W}{m^3}] \tag{5}$$

Note also that: $1\ [W/m^3] = 10^{-3}\ [mW/cm^3]$.

$\mu_r Q$ is a complex function of flux density and frequency. If a bias is applied, it is also a function of bias. Note here that μ_r is dimensionless. For the frequency in the MHz range, $\mu_r Q$ of ferrite is of the order of 10^4. [5]

The flux density is $B = \mu I / 2\pi r.$ (6)

Obviously, the maximum occurs at the inner radius

$$B_{max} = \mu I / 2\pi r_1 = \mu_0 \mu_r I / 2\pi r_1 \tag{7}$$

The relationship between flux and inductive voltage can be found by integration:

$$V = \omega \int B dA = \omega B_{\max} l r_1 \ln \frac{r_2}{r_1} \tag{8}$$

For a specified V and $l = Nd$, the maximum flux density is:

$$B_{\max} = \frac{V}{2\pi f \, N \, d \, r_1 \ln(r_2 / r_1)}, \tag{9}$$

from (5),

$$P_{d\max} = \frac{1}{4\pi\mu_0 [d \, r_1 \ln(r_2 / r_1)]^2} \cdot \frac{V^2}{N^2 f(\mu Q)} \quad [\frac{W}{m^3}] \tag{10}$$

The total power loss is simply a volume integral on account of $P_d = P_{dmax} \cdot (r_1/r)^2$.

$$P_{tot} = P_{d\max} \cdot 2\pi N d \, r_1^2 \ln(r_2 / r_1) = \frac{1}{2\mu_0 d \ln(r_2 / r_1)} \frac{V^2}{Nf(\mu Q)} \, [W] \tag{11}$$

Substituting (10), the average power loss per unit volume is:

$$P_{av} = \frac{P_{tot}}{\pi (r_2^2 - r_1^2) N d} = k P_{d\max} \tag{12}$$

where

$$k = \frac{2 \ln(r_2 / r_1)}{(r_2 / r_1)^2 - 1}$$

Now consider a numerical example. Table 5 gives the parameters of ferrite 4L2.

Table5 The $\mu_r Q$ and $\mu_r Q f$ value of 4L2

Material		4L2	
Permeability	μi	250±50	
	μrem	200	
		$\mu_r Q$	$\mu_r Q f$
2.5MHz,5mT		$25 \cdot 10^3$	$6.25 \cdot 10^{10}$
10mT		$20 \cdot 10^3$	$5 \cdot 10^{10}$
20mT		$9 \cdot 10^3$	$2.25 \cdot 10^{10}$
5MHz , 5mT		$15 \cdot 10^3$	$7.5 \cdot 10^{10}$
10mT		$11 \cdot 10^3$	$5.5 \cdot 10^{10}$
20mT		$5 \cdot 10^3$	$2.5 \cdot 10^{10}$

The $\mu_r Q$ values are quoted from the data sheet.[5] Obviously, those data are a coarse approximation and $\mu_r Q f$ are not constant. But in a common sense, for a tuning cavity with variable bias, $\mu_r Q f$ can be regarded as a constant within a limited extent of flux density. To this end, considering the flux $B_{rf} \leq 10\text{mT}$, from the Table 5, $\mu Qf = 5\times10^{10} \sim 5.5\times10^{10}$.

Substituting the geometric parameters $r_2 / r_1 = 50 / 18$, $d = 0.027\text{m}$ and $V_{max} = 8kV$, $\mu Qf = 5\times10^{10}$, then from (11),

$$P_{tot} = 2.06\times10^{-5}\, V^2 \quad [\text{W}] \quad \text{for } N = 14$$
$$P_{tot} = 1.03\times10^{-5}\, V^2 \quad [\text{W}] \quad \text{for } N = 28 \qquad (13)$$

Fig.5 shows the total power loss in the ferrite pursuant to the specified voltage ramp.

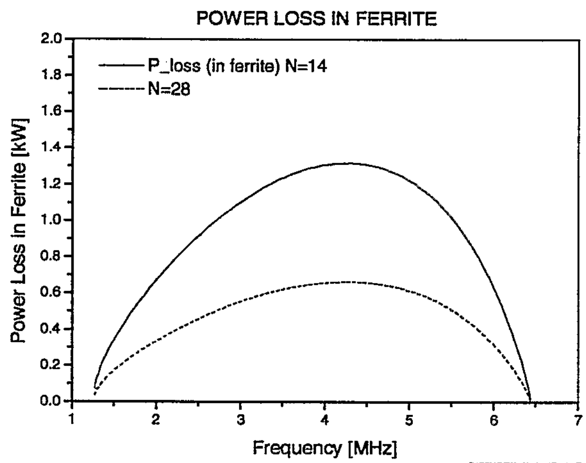

Fig.5 The total power loss in the ferrite

The maximum total loss is 1.32 kW at 4.3 MHz. This determines the minimum power requirement to the supply, i.e. the concern (a) mentioned at the start of this section. The rest concerns are

(b) The maximum loss density is, from (11), $P_{dmax} = 6.72\times10^{-4}$ $[W/m^3] = 67$ $[mW/cm^3]$. This is considered quite modest.

(c) The average power loss, from Fig.5, is 723W. Taking into account the fact that the duty cycle is 50%, the heat to be removed is only 362W. But, this amount is only the RF loss. The loss due to biasing has not been accounted for yet.

(d) The hottest spot, corresponding to the maximum loss density, has a loss of 18.4 mW/cm^3. Again, it is modest, but doesn't take biasing loss into account.

Note that above results are based on the assumption of one cavity and one gap, the toughest situation. Therefore, we can conclude that the power dissipation in the ferrite is quite modest and thus worry free.

THE BIAS PERFORMANCE OF FERRITE

In the case of bias tuning, the permeability is unequal in space and thus complicates the calculation. We have chosen the ferrite type Phillips 4L2. However, the available data are limited. Table 5 lists the relative permeability as a function of the bias.[5]

Fig.7 shows that above 250 A/m μ_r is a straight line on a log-log scale.

Below 250 A/m, the permeability changes slowly but no data between zero and 250A/m is available. In Fig.7 we use another straight line approximation. But the transition of a broken line will cause error.

Table 5

H [A/m]	μ_r
0	200
250	120
500	55
1000	25
2000	12
3000	8

For a better approximation, another fitting curve on a linear scale and for H<500A/m is shown in Fig.8.

Therefore from Fig.7 and Fig.8,

For H > 250 A/m

$$\log \mu_r = \alpha - \beta \log Hb$$

$$\mu_r = 10^{\alpha} \cdot H_b^{-\beta} \qquad (14a)$$

where $\alpha = 4.693$

$\beta = 1.093$

For H < 500 A/m

$$\mu_r = 200 - 0.35211\,H + 1.2281 \times 10^{-4}\,H^2 \qquad (14b)$$

The combined fitting curve on a log-log scale is shown in Fig.9, which displays a smoothened transition.

Since the bias field H varies along the radius, the permeability changes correspondingly. We can use above expression to estimate the average.

Note that $\mu_r = \dfrac{\Delta B}{\Delta H}$

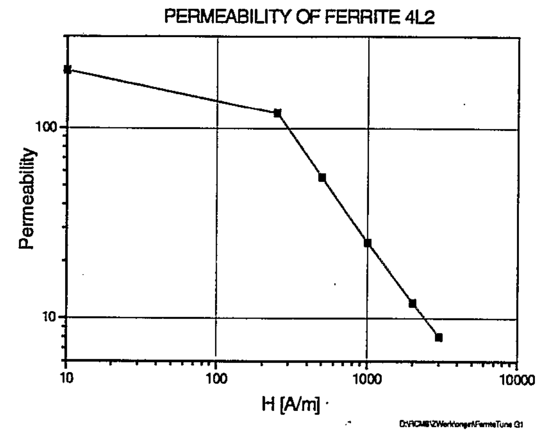

Fig. 7 Permeability vs bias

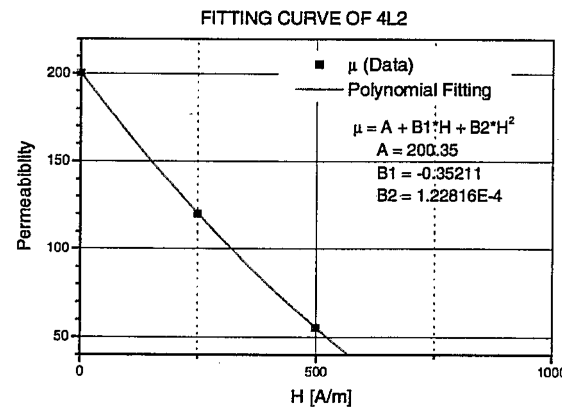

Fig. 8 Fitting curve for H < 500 A/m

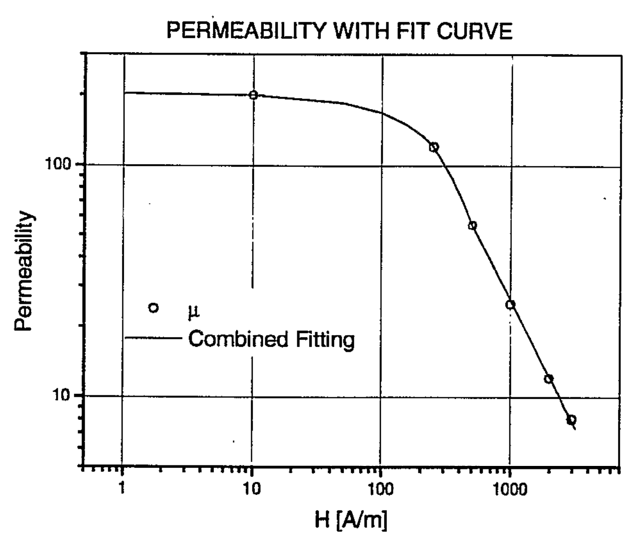

Fig.9 The permeability and its fitting curve

is a function of the bias field H_b, while ΔB and ΔH are rf quantities. For $H > 250$A/m,

$$\Delta B = \mu_0 \mu_r \, \Delta H = \mu_0 (10^{\alpha} \cdot H_b^{-\beta}) \Delta H$$

$$H_b = \frac{I_b}{2\pi r} = \frac{I_b}{2\pi r_0} \cdot \frac{r_0}{r} = H_{b0} \cdot \frac{r_0}{r}, \qquad H_{b0} = H_b \big|_{r=r_0}$$

$$\Delta H = \frac{I_{rf}}{2\pi r} = \frac{I_{rf}}{2\pi r_0} \cdot \frac{r_0}{r} = \Delta H_0 \cdot \frac{r_0}{r}, \qquad \Delta H_0 = \Delta H \big|_{r=r_0}$$

then

$$\Delta B = \mu_0 \mu_{r0} \Delta H_0 \left(\frac{r_0}{r} \right)^{1-\beta}, \qquad \mu_{r0} = 10^{\alpha} H_b^{-\beta} \Big|_{r=r_0} \tag{15}$$

where r_0 is an arbitrary reference radius. The total flux can be found from the integral:

$$\int_{r_1}^{r_2} \Delta B dr = \mu_0 \mu_{r0} \Delta H_0 \cdot \frac{r_0^{1-\beta}}{\beta} \left(r_2^{\beta} - r_1^{\beta} \right) \tag{16}$$

where r_1 and r_2 are the inner and outer radius of the ferrite ring respectively. If the permeability is uniform and equal to μ_{av}, the integral should be

$$\int_{r_1}^{r_2} \Delta B dr = \mu_0 \mu_{av} \Delta H_0 \cdot r_0 \ln \frac{r_2}{r_1} \tag{17}$$

Comparing the two expressions, the average permeability μ_{av} is found to be:

$$\mu_{av} = \mu_{r0} \cdot \frac{r_0^{-\beta}}{\beta} \cdot \frac{r_2^{\beta} - r_1^{\beta}}{\ln(r_2/r_1)} = \mu_{r0} \cdot g \tag{18}$$

$$g = \left(\frac{r_1}{r_0} \right)^{\beta} \cdot \frac{1}{\beta} \cdot \frac{\rho^{\beta} - 1}{\ln \rho}, \qquad \rho = \frac{r_2}{r_1} \tag{19}$$

g is a geometrical factor. Because of the nonlinearity, the average point is not on the center of the ring. Let's define an average point, r_{av}, where μ_r represents the average, namely the reference point has $\mu_{r0} = \mu_{av}$, or from (18) $g = 1$, then:

$$r_{av} = r_1 \left(\frac{1}{\beta} \cdot \frac{\rho^{\beta} - 1}{\ln \rho} \right)^{1/\beta} \tag{20}$$

Table 6 lists r_{av} with different ring sizes. As can be seen it is neither an arithmetical mean, nor a geometrical mean.

Table 6 The average radius r_{av} with different ring sizes

Inner Radius	cm	6.25	12.5	9
Outer Radius	cm	25	25	25
Average radius r_{av}	cm	13.62	18.07	15.72
Arithmetical Mean	cm	15.63	18.75	17
Geometrical Mean	cm	12.5	17.68	15

The above results are based on the fitting of $H > 250$ A/m. It is not precise for $H < 250$ A/m. However, with $H < 250$ A/m, the permeability changes much more slowly along the radius, thus the position chosen is less important.

For a giving biasing current, one can use r_{av} to calculate the field H and then the permeability and flux.

For a given frequency ramp, one can figure out the required ramp curve of the inductance and then the permeability. To find the required biasing field, one needs an H-μ curve. This curve is the reversal of Fig.9 and shown in Fig.10, on which the data are obtained by interpolation. From H one can figure out the biasing current and voltage as functions of time.

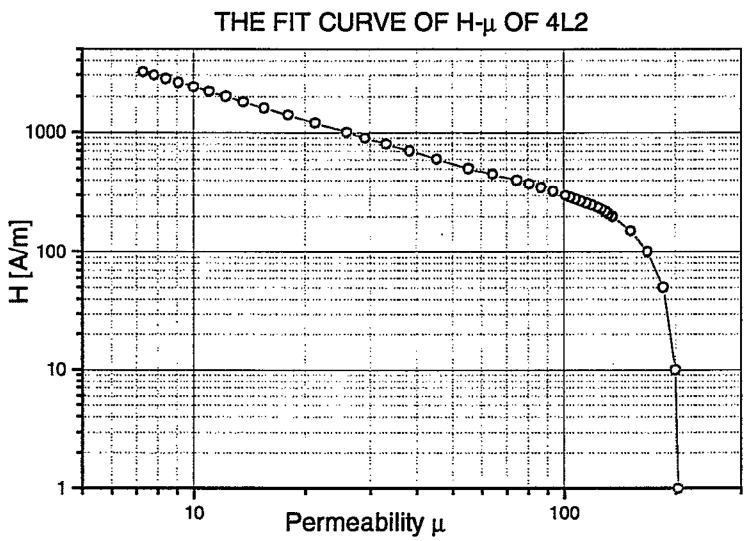

Fig. 10 A fit H-μ curve of ferrite 4L2

The sectional fitting functions of Fig.10 are as follows:

$$\begin{aligned} &\log H = 4.274 - 0.89737 \times \log \mu && (\mu < 100) \\ &H = 590 - 2.866 \times \mu && (100 < \mu < 135) \\ &H = 591 - 2.91 \times \mu && (135 < \mu) \end{aligned} \tag{21}$$

The biasing current is:

$$I_{b1}(t) = H(t)\, 2\pi\, r_{av} \tag{22}$$

The biasing voltage on the ferrite is

$$V_{b1} = -\frac{\partial \Psi}{\partial t} = -\frac{\partial}{\partial t}\int B dS = -\frac{\partial B}{\partial t} S = -\mu \frac{\partial H}{\partial t} S \tag{23}$$

where $S = N \cdot d \cdot (r_2 - r_1)$ is the whole cross section. If the bias winding uses N turns in order to reduce the bias current, then

$$I_b = I_{b1} / N \tag{24}$$

$$V_b = N\, V_{b1} \tag{25}$$

TWO CAVITY OPTION

The RCMS project requires a frequency ramp in a range of 1:5. The ferrite of 4L2 has its permeability varied from 200 to 8 (see Table 5), or a ratio of 25, with a maximum biasing field of 3000A/m. Without stray inductance, the inductance of ferrite itself can tune a frequency of 1:5, which just meets the requirement. However, since stray inductance is inevitable, as shown in expression (4), the possible tuning range is only about 1:3. Therefore, it seems necessary to have two cavities to cover whole band.

Considering Case 2 in Table 1 as an example, the frequency range is from 1.273 to 6.45. Let's allocate the frequency as shown in Table 7.

Table 7

	Unit	Low Band	High Band
Minimum Freq.	MHz	1.273	2.15
Maximum Freq.	MHz	3.82	6.45
Ratio of Freq.		1:3	1:3
Maximum Inductance	μH	16.5	16.5
Minimum Inductance	μH	≈1.62	≈1.62
Capacitance	pF	950	330

The required bias current and voltage are shown on Fig. 11 and 12.

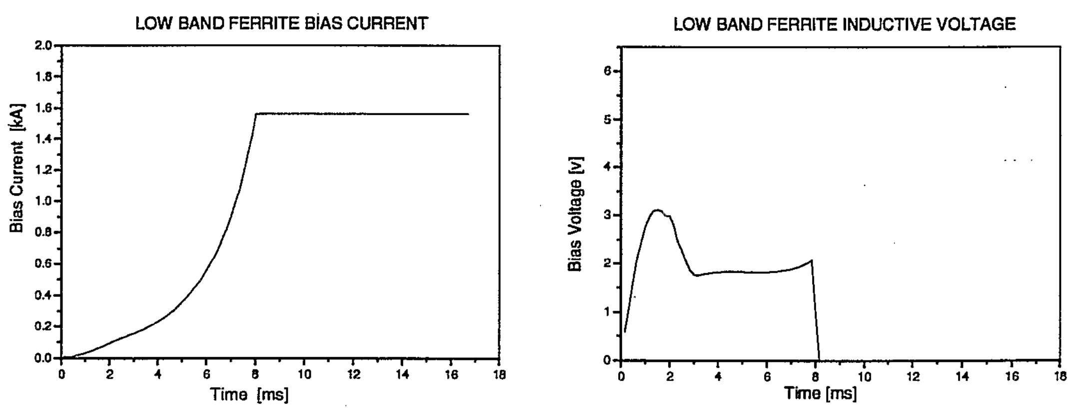

Fig.11 Required bias current and voltage for low band

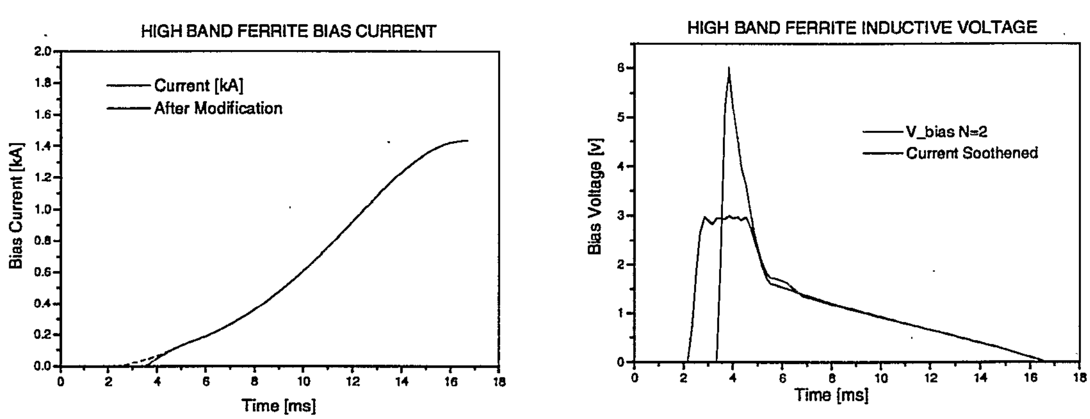

Fig.12 Required bias current and voltage for high band

Note the results are those for perfect tuning and the bias winding has 2 turns. For the high band (see the red line in Fig.12), there is a voltage peak of 6 v. When the bias current is slightly modified to make it smooth (see the blue line), the inductive voltage is reduced to only 3v. The bias modification will cause the frequency to go off resonance. However, there is an overlap band between 2.15 to 3.82 MHz, which implies that either of the two cavities on resonance is adequate.

The two cavities need two independent power supplies with 3 volt each. The current is between zero to 1560 A. It can employ an AC current of less than 1000A power supply with a DC bias of about 800 A. The supply would be programmable. The program has to be decided experimentally to fit the tuning requirement.

A series resonant circuit is also possible to apply for saving power. However, since the current is far from a sine wave, it is complex and the real circuit has to be determined experimentally.

Since all frequencies can be tuned to resonance, the RF driver power is for compensating the ferrite loss only and is 1.32kW maximum. Therefore, two amplifiers with 1.5kW each would be satisfactory.

ONE CAVITY OPTION

As far as cost is concerned, it is strongly desirable to reduce the number of cavities. To this end, one cavity option is of special interest. Correspondingly, the lattice of RCMS has been modified so that the available space for one cavity increases additional 46 cm to a total effective length of 131 cm as shown in Case 3 of Table 1. [6]

The preceding section indicates that the existence of stray inductance will reduce significantly the coverage of the tunable band. In order to meet the need of a tuning ratio of 1:5, one can do the following. (a) Minimize the stray inductance; (b) Maximize the inductance contributed by the ferrite; (c) Extend the bias field to beyond 3000A/m so as to reduce the permeability further.

The extra length 46cm of the cavity can include 14 extra ferrite rings. So the total number of rings will be 28. Then the inductance of ferrite is $L = 31\ \mu$H.

A similar calculation for the stray inductance inside the cavity results in 0.25 μH. The stray inductance due to connector line remains the same, i.e. around 0.32 to 0.5 μH. A careful mechanical design is necessary to minimize the stray inductance. The capacitor should be as close to the cavity as possible. Assume the total stray inductance is 0.57 μH. Thus the tunable range is:

$$\frac{f_{\max}}{f_{\min}} = \sqrt{\frac{L_{\max}}{L_{\min}}} \tag{25}$$

With a maximum inductance of $L_{max} = 31.57\ \mu$H, Table 8 gives the results.

Table 8

Bias field	A/m	0	3000	4000*	5000*
Relative Permeability		200	8	5.70	4.47
Inductance of ferrite	µH	31	1.24	0.88	0.69

Stray inductance	μH	0.57	0.57	0.57	0.57
Total inductance	μH	31.57	1.81	1.45	1.26
Tunable ratio			4.17	4.66	5

*The permeability in this column is the extrapolated value.

In order to cover a range of 1:5, the bias field needs to be 5000A/m. It is unlikely to be practical. Thus one has to consider a partial tuning with two frequency edges being left off resonance.

Assuming the maximum bias field is 3000A/m, the tunable ratio is 4.17. After optimization, the tunable band is located from 1.48 MHz to 6.18 MHz, beyond that is off resonance. Fig.13 shows the tuning curve and the required ramp curve.

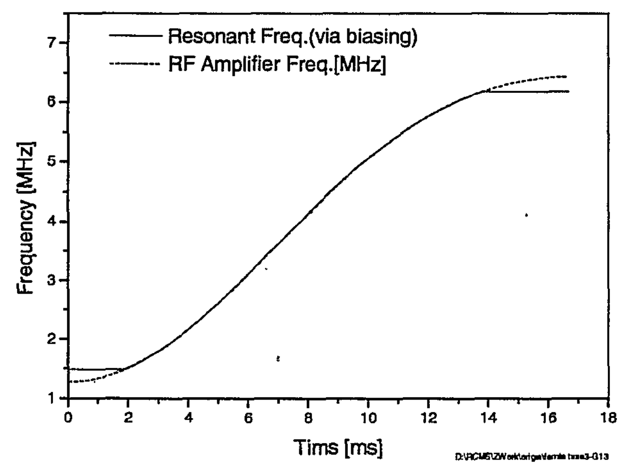

Fig. 13 Partial tuning with maximum bias 3000 A/m

The capacitance is 365pF. Let's put also an external resistance of 5kOhm so as to reduce the Q. The required driver power and current are shown in Figs. 14 - 15.

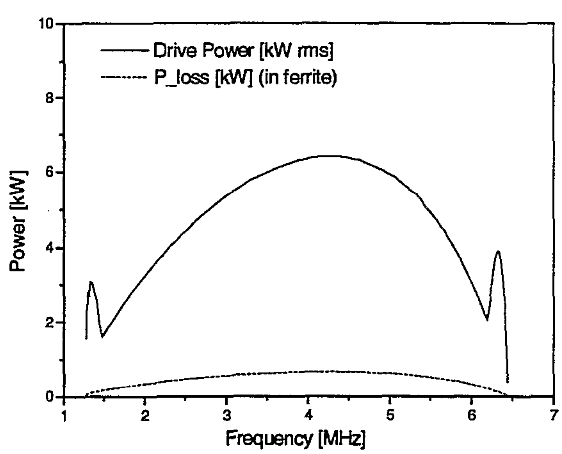

Fig.14 Drive power and ferrite loss

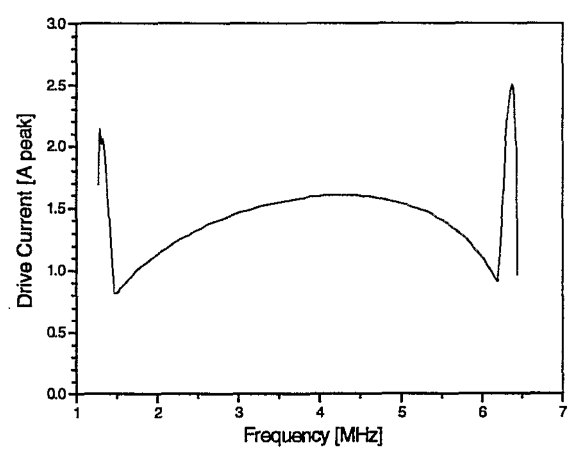

Fig.15 Drive current

The amplifier requires a minimum power of 6.4 kW. But the peak voltage is 8kv and peak current is 2.5A. So the reactive power required is 20kVA peak or 10kVA rms. Also shown is the loss in the ferrite. Evidently, most power is lost in the external resistance. The largest current is due to a reactive capacitance current.

We can reduce the loss by decreasing the external load. But, the reactive power can not be reduced. In order to reduce the reactive power, we extend the biasing field from 3000 A/m to 4000 A/m. Table 9 shows the required bias current, which has taken into account that r_{av} = 15.57cm from Table 6.

Table 9

Maximum Field		3000 A/m	4000 A/m
Number of Turns of Bias winding	1	2963 A	3951 A
	2	1482 A	1975 A

Note that the bias power source may involve a DC bias current plus an AC ramp current. An option of 4000 A/m with two turns winding can be managed with an AC source of less than 1000 amperes.

To this end, we can extend the tuning ratio to 1:4.66 as shown in Table 8 and then narrow the non-resonant region. After optimization, we choose the following parameters: capacitance C = 435pF, resonant band from 1.257MHz to 6.329 MHz, external load R = 10kΩ. The results are plotted in Figs.16 and 17.

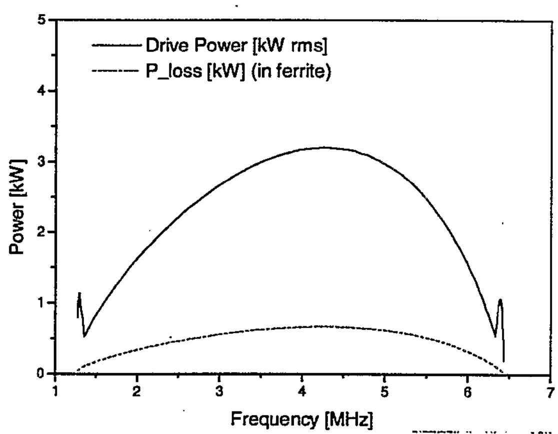

Fig. 16 Drive power and ferrite loss

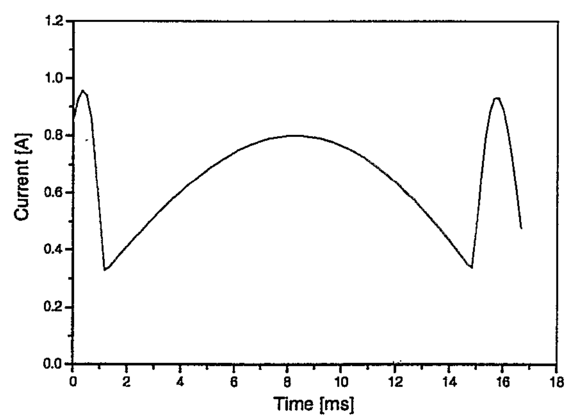

Fig.17 Drive current

We see that the real power is 3.2 kW maximum. The maximum driver current is less than 1 Ampere and thus the reactive power is 8kVA peak or 4kVA rms. Therefore one 4kW amplifier seems satisfactory.

SUMMARY

It has been verified that the loss inside the ferrite is quite modest. However, it has also been shown that any use off resonance would significantly increase the power requirement. We then focused our effort to the tunable cavity with variable bias field. A tuning range of 1 to 5 is a big challenge. The unavoidable stray inductance enhances the difficulty.

To satisfy the tuning range, a two-cavity option was calculated with the original "short" cavity. One cavity option with a longer cavity has also been calculated. Both are workable and the parameters are summarized in Table 10 for comparison.

Here we assumed that the bias winding has two turns. For the one cavity option, two different bias fields are also listed as possible arrangements.

Table 10 Comparison of different options

Option (Number of cavity)			Two		One	One
			Cav 1	Cav 2		
Cavity length		cm	85	85	131	131
# of ferrite rings			14	14	28	28
Bias Current	DC AC	A	800 800	800 800	800 800	1000 1000
Bias Voltage		v	3	3	3	3
Tunable range	Start End	MHz	1.273 3.82	2.15 6.45	1.48 6.18	1.26 6.33
Capacitance		pF	950	330	365	435
RF Driver	Voltage	kV	8	8	8	8
	Current	A			2.5	1
	Power(rms)	kVA	1.5	1.5	10	4

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