Fermilab

$\bar{p}$ Note #398

# PPA CAVITY POWER LOSSES

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# F.P.A. Cavity power losses

The losses in a magnetic material under R.f excitation can be described by the Q factor or by the loss angle $\delta$ of material. A complex permeability $\mu_r = \mu' - j\mu''$ is often introduced as well, $\mu'' \neq 0$ then implies a phase lag of $B_r$ with respect to $H_r$, and $\mu''$ is a measure of the losses. By definition Q, $\delta$, $\mu'$ and $\mu''$ are interrelated by

$$\frac{1}{Q} = \tan\delta = \mu''/\mu' \qquad (1)$$

The power loss per unit volume $P$ is given by

$$P = \frac{\omega \hat{B}_r \hat{H}_r}{2Q} = \frac{1}{2}\omega\mu''\mu_0 \hat{H}_r^2 = \frac{\pi f \hat{B}_r^2}{\mu_r \mu_0 Q} \qquad (2)$$

(Where it is assumed that $\mu''/\mu' = \frac{1}{Q} \ll 1$)

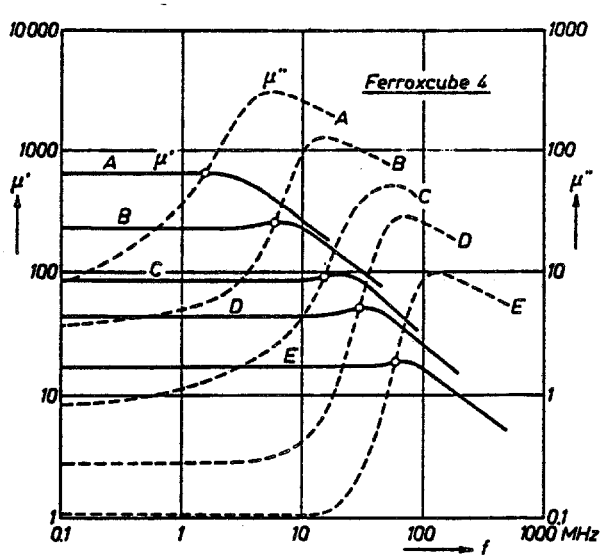



Fig. 16. Real part $\mu'$ and imaginary part $\mu''$ of the permeability as a function of frequency for ferroxcube 4A, B, C, D and E [10]. The peak in $\mu''$ is due to ferromagnetic resonance absorption. The approach of resonance is marked by the frequency at which $\tan\delta = 0.1$ ($Q = \mu'/\mu'' = 10$). As the scales for $\mu'$ and $\mu''$ differ by a factor of 10, this frequency is found at the intersection of the $\mu'$ and the $\mu''$ curves (see also Table III).

Fig 16 Show the $\mu'$ and $\mu''$ varies with frequency. The loss factor (for small $\hat{B}_r$) in all ferrites shows a large increase at some frequency and this increase sets in at higher frequencies the harder the ferrite. But Q $\delta$ and $\mu''$ are not "material constant". they are affected by the

amplitudes of the r.f. magnetic field and flux density $\hat{B}_\sim$.

$$\tilde{V}_\sim = \omega A \hat{B}_\sim \qquad (\hat{V}_\sim \text{ is R.f. Voltage})$$

$$\hat{B}_\sim = \hat{V}_\sim / \omega A = \hat{V}_\sim / 2\pi f A$$

$$\therefore \; p = \frac{\pi f (\hat{V}_\sim / 2\pi f A)^2}{\mu_0 \mu_r Q} = \frac{\hat{V}_\sim^2}{4\pi \mu_r \mu_0 Q f A^2} = \frac{\hat{V}_\sim^2}{2\mu_0 \mu_r Q \omega A^2} \qquad (3)$$

d) The value of $\mu_r Q\omega$

As we have seen before it is the value of $\mu_r Q\omega$ that is required to be large. This value is shown in *fig. 17*

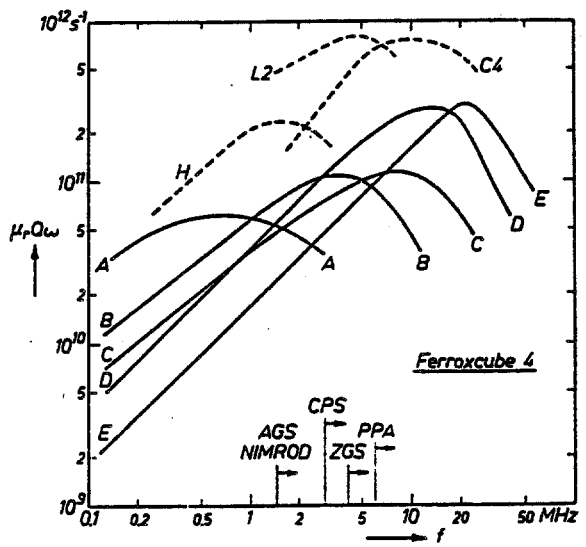



Fig. 17. $\mu_r Q\omega$ as a function of the frequency $f$ for the five grades of ferroxcube 4A, B, C, D and E (unpolarized, and for vanishing $\hat{B}_\sim$), for ferroxcube 4H (developed for the AGS and the CPS), and for some more recently developed materials, 4L2 and 4C4. The lowest frequency of the accelerating voltage in each of the machines (cf. Table V) is also indicated. (The lowest frequency indicated for the PPA refers to the cavity proper and not to the drift tube.)

The P.P.A Cavity's ferrites are ferroxcube 4C. It has four sets of ferrites, each one has ten ferrites. Two sets are parallel. The ferrite dimensions are:

OD 500 mm

ID 300 mm

thickness 25 mm

(see Fig 4 )

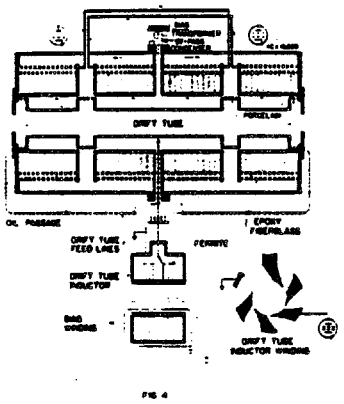
Cross sectional Area $\left(\frac{500-300}{2}\right) \times 25 = 2500\ mm^2 = 2.5 \times 10^{-3}\ m^2$

One set (10 cores) $A = 2.5 \times 10^{-3} \times 10 = 25 \times 10^{-3}\ m^2$

One set Volume $V = 25 \times 10^{-3} \times 2\pi \left(\frac{0.5+0.3}{2 \times 2}\right) = 0.03146\ m^3$

P.P.A Cavity has two tubes working in push-pull. tube's output R.F power can be calculated. From equation (3) The power losses in ferrites can be calculated. The result

are in Table I, II III. at 7.5 MHz and 2.44 MHz Separately. It can be seen that the higher the R.F. Voltage (magnetic field flux density $\hat{B}_r$) is, the larger the different between experimental and calculation is. There are some reasons. first: We used $\mu_r Q \omega$ (show in Fig 17) are value for vanishing $\hat{B}_r$, but in this case $\hat{B}_{r\,max}$ is about 200GS; Second, we assumed that $\mu_r Q \omega$ is constant. this is not true; when $\hat{B}_r$ increases the $\mu_r Q \omega$ will decrease. from Fig 3.19.14 when $\hat{B}_{r2}$ is two and a half times as high as $\hat{B}_{r1}$ The power loss density $P_2$ is ten times as large as $P_1$. It means when $\hat{B}_r$ is large enough equation (3) have to modify. third, Experimental data included other power losses, such as capacitor, copper losses and so on.



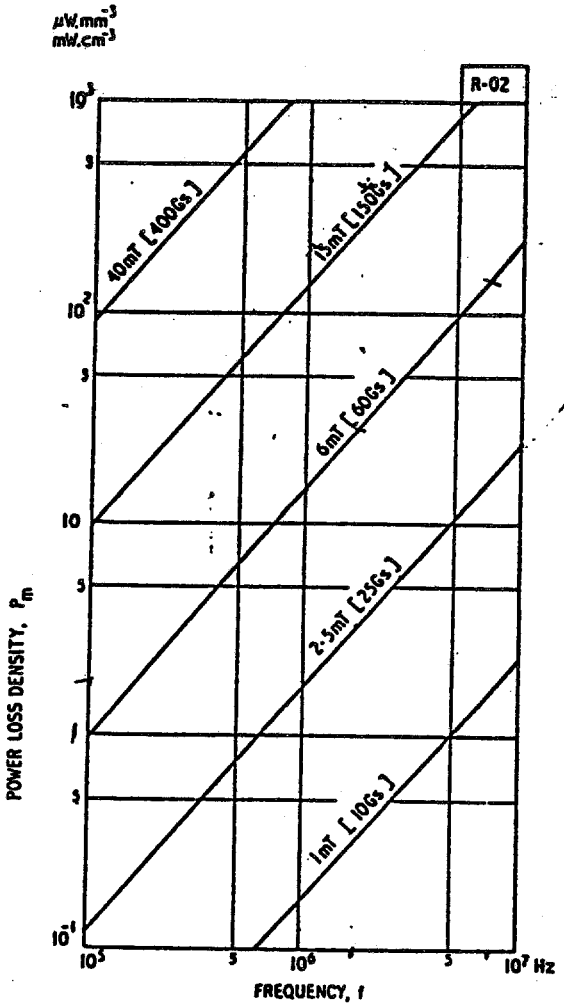



Fig. 3.19.14

According to Fig 3.19.14 equation (3) right side time a coefficient a. (a=1.6), the results are showen in Fig 5. essentially "a" is a function of $\hat{B}_r$.

TABLE I power losses in half P.P.A. cavity Ferrites at 2.45MHz (4CW10000 tube)
$\mu_r Q \omega = 5.5 \times 10^{10} s^{-1}$ modified coefficient $\alpha = 1.6$

| $\hat{V}_{RF}$(kV) | $\hat{I}_p$(A) | $\theta^{(\circ)}$ | $I_0$(A) | $\hat{I}_{A1}$(A) | R(Ω) | Power losses (KW) experiment | calculation | modified |
|---|---|---|---|---|---|---|---|---|
| 1.5 | 5 | 67 | 1.22 | 2.12 | 707.5 | 1.57 | 1.636 | 2.617 |
| 2.7 | 11.5 | 68.5 | 2.84 | 4.93 | 547.7 | 6.656 | 5.29 | 8.464 |
| 3.225 | 13 | 72 | 3.37 | 5.77 | 558.9 | 9.304 | 7.56 | 12.096 |
| 3.675 | 19 | 72 | 4.92 | 8.44 | 435.4 | 15.507 | 9.82 | 15.71 |
| 4.125 | 23 | 72 | 5.96 | 10.21 | 404 | 21.057 | 12.37 | 19.79 |
| 4.8 | 28 | 81 | 8.09 | 13.3 | 360.7 | 31.920 | 16.745 | 26.79 |
| 5.175 | 31.5 | 82 | 9.19 | 15.06 | 343.6 | 38.765 | 19.47 | 30.4 |
| 5.225 | 31.5 | 82 | 9.19 | 15.06 | 348.6 | 39.532 | 20.04 | 32 |

TABLE II power losses in half P.P.A cavity Ferrites at 2.411MHz (4CW25000 tube)
$\mu_r Q \omega = 5.5 \times 10^{10} s^{-1}$ modified coefficient $\alpha = 1.6$

| $\hat{V}_{RF}$(kV) | $\hat{I}_p$(A) | $\theta^{(\circ)}$ | $I_0$(A) | $\hat{I}_{A1}$(A) | R(Ω) | Power losses (KW) experiment | Calculation | modified |
|---|---|---|---|---|---|---|---|---|
| 5.625 | 37.95 | 79 | 10.74 | 17.8 | 316 | 50.06 | 23.2 | 37.12 |
| 6.375 | 42.7 | 80 | 12.2 | 20.15 | 316.4 | 64.23 | 29.56 | 47.3 |
| 6.935 | 50.6 | 84 | 15.13 | 24.5 | 283.16 | 85.00 | 35.02 | 56 |
| 7.125 | 53.8 | 85 | 16.25 | 26.2 | 272 | 93.36 | 36.87 | 59 |
| 7.500 | 53.76 | 85 | 16.2 | 26.15 | 287.4 | 97.88 | 40.9 | 65 |

* TABLE III power losses in half P.P.A. cavity Ferrites at 7.5MHz (4CW10000 tube)
$\mu_r Q \omega = 1.1 \times 10^{11} s^{-1}$ modified coefficient $\alpha = 1.6$

| $V_{RF}$(kV) | $\hat{I}_p$(A) | $\theta^{(\circ)}$ | $I_0$(A) | $\hat{I}_{A1}$(A) | R(Ω) | Power losses (KW) experiment | calculation | modified |
|---|---|---|---|---|---|---|---|---|
| 4.7 | 11.6 | 90° | 3.5 | 5.8 | 810 | 13.6 | 8.03 | 12.8 |
| 6.0 | 17.88 | 90 | 5.3 | 8.94 | 671 | 26.8 | 13.1 | 20.96 |
| 6.6 | 20.0 | 90 | 6.1 | 10.0 | 670 | 33.6 | 15.8 | 25.3 |
| 7.2 | 24.4 | 90 | 7.5 | 12.2 | 598 | 44.7 | 18.85 | 30.16 |

* 7.5MH experiment Data got by J Bridges

It can be seen in equation (3) that the power loss per unit Volume P is inversely proportional to $\mu_r Q\omega$. Fig 17 shows The $\mu_r Q\omega$ as a function of the frequency has a maximum Value at different point to different material. For PPA Cavity Ferroxcube 4C is used. The maximum Value of the $\mu_r Q\omega$ is at about 10MHz. When frequency moves away from this point. the $\mu_r Q\omega$ will decrease. It showes when frequency decreases from 7.5MHz to 2.45MHz, The $\mu_r Q\omega$ decreases from $8.1\times10^{11} s^{-1}$ to $5.5\times10^{10} s^{-1}$. It means that when the frequency Varies from 7.5MHz to 2.45MHz. If we want to get same R.F. Voltage we have to input ~~twice times~~ power. This result corresponds with experiment very well. For 2.5MHz. The best material is ferroxcube 4H. The power losses is only ⅓ as much as 4C.

Using Bias current to polarize ferrite can tune the resonant frequency. but the $\mu_r Q\omega$ curve will move to the right and the maximum value will be down. Therefore If It is working at left side of maximum when polarizing ferrite the $\mu_r Q\omega$ is always down The power loss per unit volume will increase.

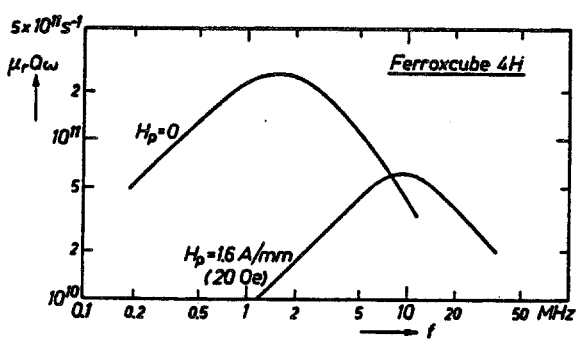



Fig. 18. $\mu_r Q\omega$ as a function of the frequency $f$ for ferroxcube 4H (for vanishing $\hat{H}_-$), in the unpolarized state and in a polarizing field of 1.6 A/mm (20 Oe).

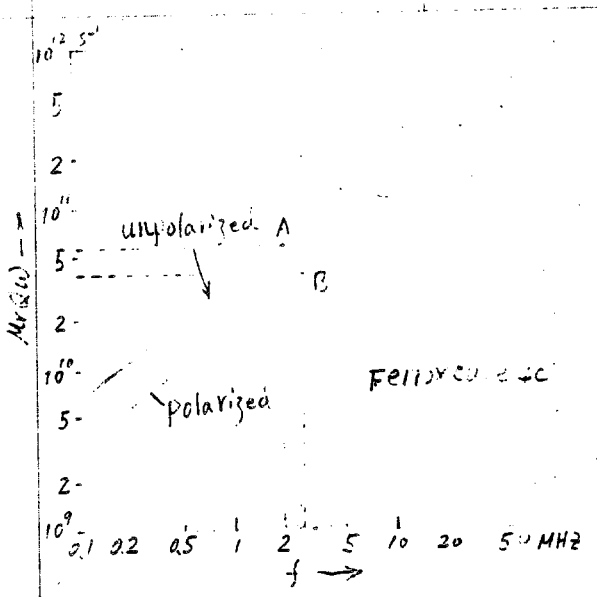



Fig 19 $\mu_r Q\omega$ as a function of the frequency f for ferroxcube 4C (for vanishing $P_a$) in the unpolarized state and in a polarized state.

The P.P.A cavity is operating at 2.5 MHz. this frequency is at the left side of maximum so when in a polarized state The $\mu_r Q\omega$ will be lower than in a unpolarized state. (point A to point B) at The Same power losses The R.F. Voltage Will decrease.

Fig 20(a) and Fig 20(b) Show the R.F. Voltag in a unpolarized state and in a polarized state separately.

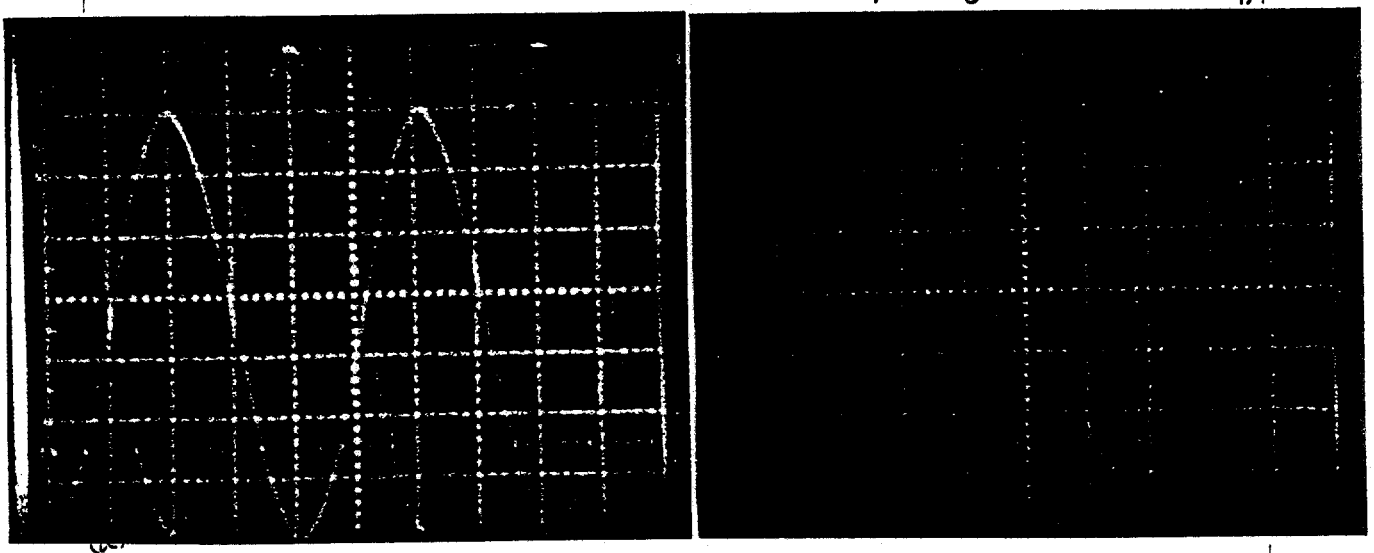
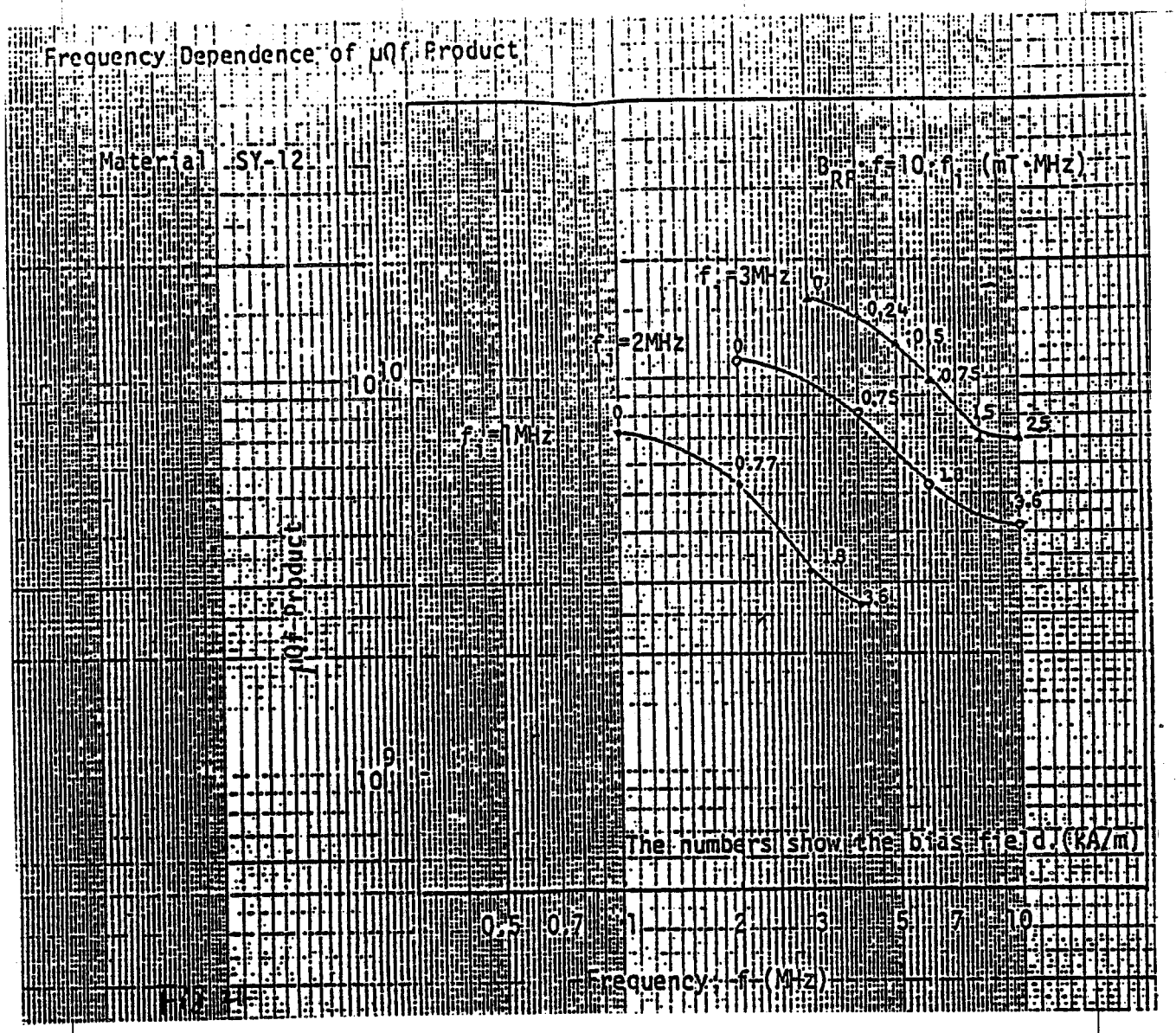


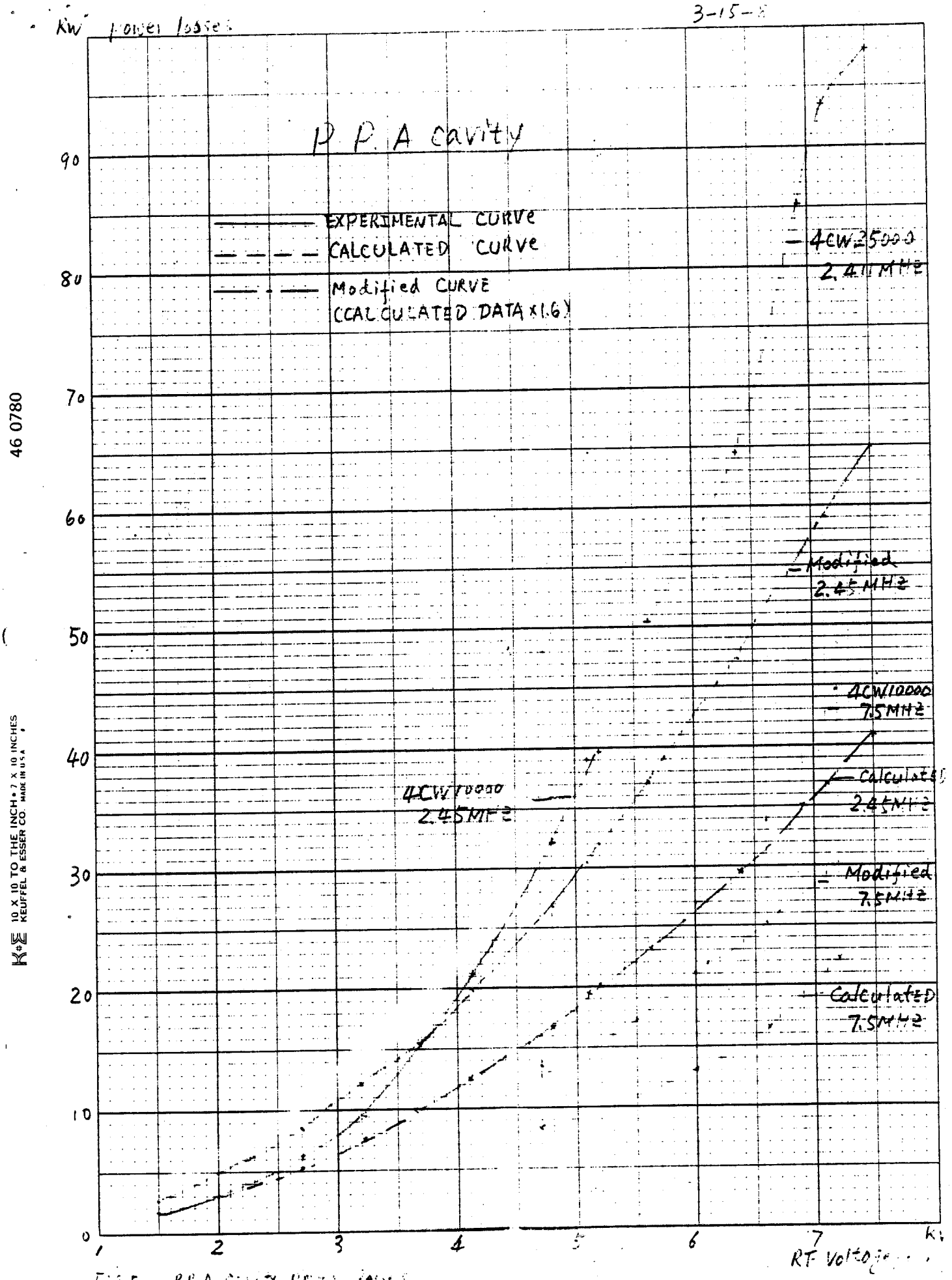
Fig 20 R.F. Voltage from anode to ground. bias current is 175A
20 (a) in a unpolarized state f=2.42MHz 20(b) in a polarized state f=2.53MHz

There is other material SY-12. It's character looks like the Ferroxcube 4C. Fig 21 Shows when polarized ferrite the f and $\mu_r Q\omega$ Varies with the bias field.

Conclusion: In order to get same R.F. Voltage The input power at 2.5MHz have to be about twice as much as input power at 7.5MHz. When input power is constant R.F. Voltage in a polarized state is less than in a unpolarized state.




If P.P.A cavity ferrites material ferroxcube 4C is replaced by 4H. only about 1/3 input RF power is required to get same R.F. Voltage so that 4CW10000 tube can still be used. So far. cavity has been changed 4CW25000 tube for 4CW10000 tube. In future If ferroxcube was used in P.P.A cavity at 2.5MHz. The R.F. Voltage would be much higher. or only one cavity might be required in Mainring. The working frequency (2.5MHz) is at right side of maximum μQW value of 4H. It is possible that when input power is the same The R.F. Voltage in a polarized state is not less than in unpolarized state. It depends on bias field.

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