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Some Thoughts for the RF System of the AGS

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1. INTRODUCTION.

This paper is not a Tech. Note and should be considered as a series of simple and fundamental considerations that allow to set those boundary conditions for the RF System that are dictated by the AGS Upgrading Program.

As a first step the AGS (Upgraded) plus the Booster were considered as a whole system where the Booster injects the particles at one GeV.

Under the above hypotheses we consider the limiting case where all the particles circulating into the Booster are nicely injected into the AGS. The parameter list on Section 2 reflects this situation.

During the last two meetings it was emphasized that in the Booster the number of particles per bunch could be higher while a reduction of a good factor of two should be expected for the AGS. As will be clear later on, the charge per bunch influences primarily the choice of the tube in the power amplifiers while the cavity design depends upon this parameter only marginally. This means that we will not modify the quoted parameter list because once the conceptual design of the cavity - power amplifier is made then a reduction of the particles per bunch would suggest only the choice of a smaller tube.

Studying the parameter list it becomes also clear that apart form the operating frequency range, the cavity-amplifier blocks for the Booster and the AGS can be made practically equal.

So if the AGS RF problem is solved then also the RF for the Booster is in good shape.

2) FUNDAMENTAL PARAMETERS.

	Booster		AGS
N = Particles per bunch.	10^{13}		10^{13}
n = Number of bunches.	3		12
q = Charge per bunch (Coulomb)	$1.6\ 10^{-6}$		$1.6\ 10^{-6}$
Q = Total charge. (Coulomb)	$4.8\ 10^{-6}$		$1.92\ 10^{-5}$
r = Average radius. (Meters)	32.114		128.456
β = Normalized speed. (1 GeV)		0.875	
$I_{av} = \frac{Q\beta C}{2\pi r}$ = Average current. (A)		6.240	
h = Harmonic number.	3		12
$I_1 = \frac{2q}{(2\pi r/hc\beta)} = 2\ I_{av}$ = Max. first harm. component. (A)		12.480	
$\nu = \frac{hC\beta}{2\pi r}$ = RF. Frequency. (MHz)		3.90	
$\tau = 0.25/\nu$ Minimum length of the bunch. (sec)	$1.06\ 10^{-7}$		$6.4\ 10^{-8}$
$I_p = q/\tau$ Maximum peak current. (A)	14.9		25

3) BEAM LOADING

A parallel tuned circuit can give a sufficiently good approximation for simulating the behaviour of the cavity in the neighborhood of a resonance.

Assuming that $\bar{I}_a$ is the amplifier current transferred to the gap while $\bar{I}_b$ is the beam current then the equivalent scheme is as in Fig. 3-1

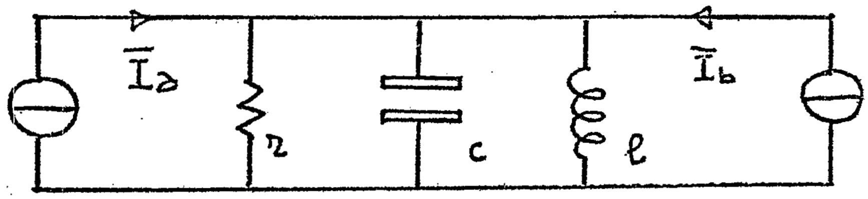

FIG. 3-1 .

where l, c, r are the cavity coupling system equivalent parameters. It should be emphasized that r includes both the cavity and the power amplifier output impedance as seen by the gap.

Let us call ϕs the phase of the synchronous particle measured off peak. Then the first harmonic component of the beam current $\bar{I}_b$ should be:

$$\bar{I}_b = I_b \, e^{j(\phi+\pi-\phi_s)}$$

as shown in Fig. 3-2

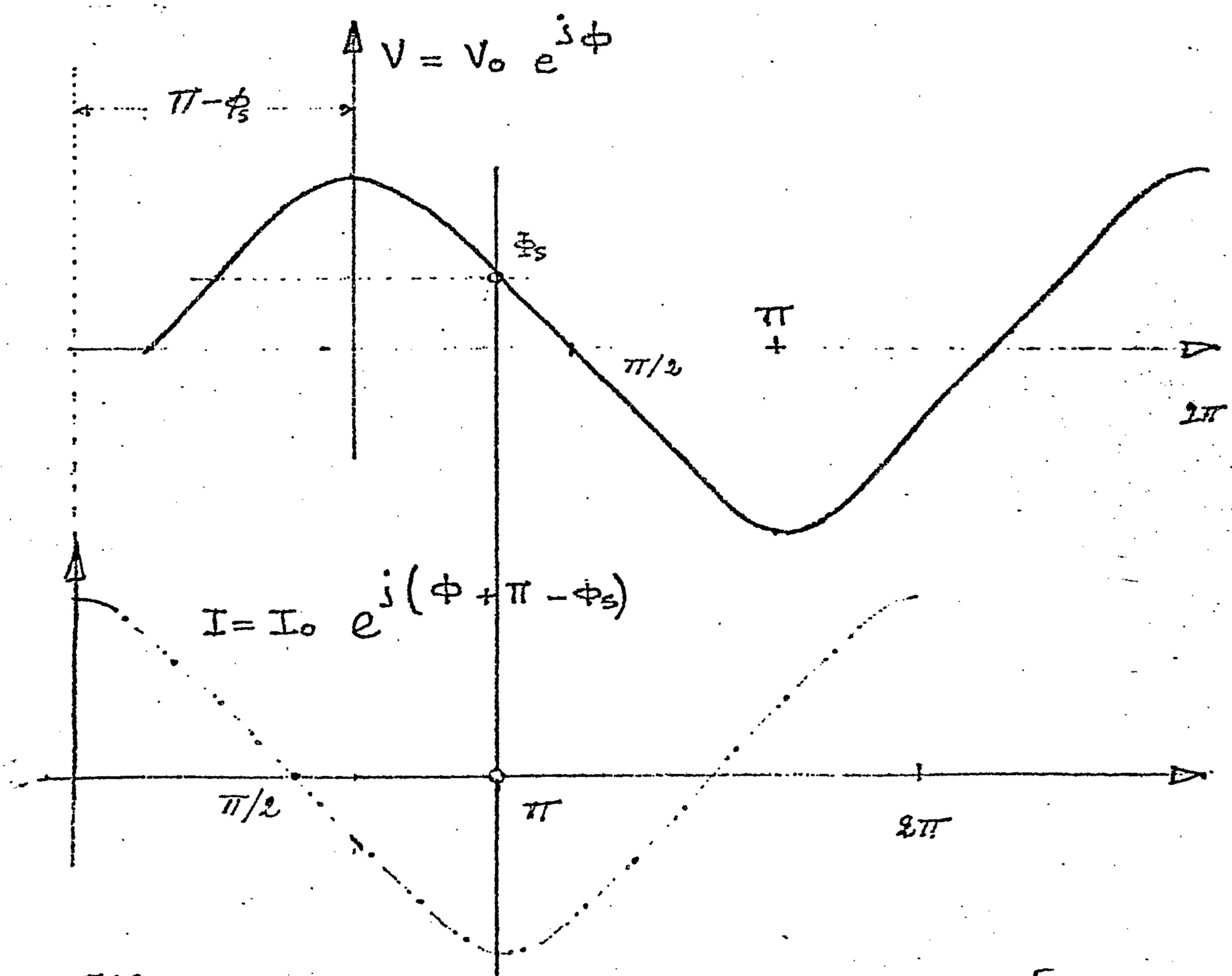

FIG 3-2

because the minima of the first harmonic should be coincident, in time, with the synchronous particle.

If we put $\bar{I}_a = I_a e^{j\phi_a}$ and V is the gap voltage then we have:

$$\left[\frac{1}{r} + j(\omega c - \frac{1}{\omega l})\right] V = I_a e^{j\phi_a} + I_b e^{j(\pi - \phi_s)} \qquad (3\text{-}1)$$

solving we obtain:

$$\frac{V}{r} = I_a \cos \phi_a - I_b \cos \phi_s$$

$$(\omega c - \frac{1}{\omega l}) V = I_a \sin \phi_a + I_b \sin \phi_s$$

If we want the current $\bar{I}_a$ in phase with the voltage then ϕa should be zero and we have:

$$I_a = \frac{V}{r} + I_b \cos \phi_s$$
$$c = \frac{1}{\omega^2 l} + \frac{I_b \sin \phi_s}{\omega V} \qquad (3\text{-}2)$$

because the tuning capacity required without beam is equal to $1/\omega^2 l$ then it follows that the extra capacity

$$\Delta c = \frac{I_b \sin \phi_s}{\omega V} \qquad (3\text{-}3)$$

compensates the quadrature component of the beam current.

Using different words we can say that for neutralizing the effect of the quadrature component of the beam the total susceptance B of the cavity should be equal to $(I_b \sin \phi_s)/V$ instead of being equal to zero. (Normal tuning.)

It is rather evident that below the transistion ϕ_s is negative and the capacity Δc should be subtracted. (We recall that in steady state conditions instead of negative capacitance a positive inductor can be used.)

4) THE ROBINSON INSTABILITY.

Because this topic is well known we will not repeat what is written in so many excellent papers.

Instead we can follow the straightforward idea that E. Raka pointed out to me last October for arriving quickly at the final formula.

The phase stability is obviously lost when the beam rides the crest of the amplifier voltage. Now in order to compensate for the quadrature component of the beam current we detune the cavity (accordingly with 3-2) and the amplifier induced voltage moves toward the beam. When the amplifier induced voltage is exactly opposite to the first harmonic of the beam current then the stability is lost (Robinson effect).

The amplifier induced voltage is:

$$\bar{V}\ \frac{1}{r} + j\,\frac{I_b \sin\phi_s}{V_c} = \frac{V_c}{r} + I_b \cos\phi_s \tag{4-1}$$

Where now $\bar{V}$ is the total gap vector voltage we are looking for and V_c is the assigned cavity voltage.

From Eq. (4-1) it is evident that the phase ψ of the voltage $\bar{V}$ can be defined as follows:

$$\mathrm{Tan}\ \psi = -\frac{r\ I_b \sin\phi_s}{V_c} \tag{4-2}$$

Because the beam current has phase equal to $-\phi_s$ then it follows that the limit R_r is reached when $\psi = -\phi_s$ and we obtain:

$$R_r \leqslant \frac{V_c}{I_b \cos\phi_s} \tag{4-3}$$

where R_r is now the maximum value allowed for the total gap shunt impedance. (And it is evident that R_r increases with the square of the voltage if the power delivered to the beam has to remain constant.)

As a consequence of Eq. (4-3) the amplifier current becomes:

$$I_a = \frac{V_c}{r} + I_b \cos\phi_s = 2\ I_b \cos\phi_s$$

5) IMPLICATIONS

We consider the AGS case leaving unchanged the actual cavities and we obtain:

Energy range.	$\Delta E = 29\ 10^9$ volt
Acc. time	$\Delta T = 0.5$
Number of cavities.	$NC = 10$
Number of gaps per cavity.	$NG = 4$
Total capacity per gap.	$CG = 300\ 10^{-12}$ farad
Synchronous phase (off peak).	$\phi_s = 60°$
Peak voltage per gap.	$Vc = 10\ 10^3$ volt
Shunt impedance per gap.	$Rs = 10\ 10^3$ ohm
Rings of ferrite per gap.	$NF = 12$

Total power cavity:

$$P_t = \frac{(Vc)^2}{2Rs} + \frac{Q \cdot \Delta E}{\Delta t} \cdot \frac{1}{NC} = 116.360 \text{ kW}$$

Robinson resistance per gap:

$$R_r = \frac{Vc}{I_b \cos\Phi_s} = 1602 \text{ ohm}$$

and taking into account the inherent losses of the cavity the real resistor needed in parallel is equal to 1.908 kΩ.

This resistor demands ~ 26.205 kW of power per gap and the total power per cavity needed for preventing the Robinson effect amounts to 104.82. Consequently the total power needed per cavity would be ~ 216 kW.

If we still assume that each gap behaves as the input port of a parallel circuit then the voltage drop ΔV due to a rectangular beam is as follows:

$$\Delta V = -\frac{I_p}{\omega o}\; e^{-\frac{t}{2rc}} \sin \omega t; \; 0 \leqslant t \leqslant \tau \tag{5-1}$$

where if ωo is the resonant frequency of the cavity then $\omega = \omega o\ (1-1/(2\omega orc)^2)^{1/2}$, I_p and τ are the intensity and the duration of the beam.

Assuming: $I_p = 25$, $\tau = 6.41\ 10^{-8}$, $r = 1602$, $c = 300$, $\omega o = 2\pi \cdot 4\ 10^6$ we obtain:

$$\omega = 0.998\ \omega o = 2.5069\ 10^7 \text{ rad/sec}$$
$$\Delta V = 3.324\ 10^3\ e^{-(t/9.6\ 10^{-7})} \cdot \sin\omega t$$

for $t = \tau$ then $\Delta V \cong 3100$ volt per gap. (More than 30%).

These very simple calculations show that some major changes are mandatory.

6) EXERCISE

We assume to realize a cavity push-pull driven with a total voltage of 50 kV.

In this case we need only 8 cavities and the power per cavity will be as follows.

$$W = \frac{1}{8} \frac{Q \cdot E}{\Delta t} + \frac{V^2}{2\ Req} = 139 + 25 = 164 \text{ kW.}$$

where we assumed that the physical shunt impedance of each cavity is near to 50 kΩ.

The minimum value of the total shunt impedance required for preventing the Robinson instability is equal to:

$$R_r = \frac{V}{I_b \cos \phi_s} = \frac{50\ 10^3}{6.4} = 7812 \text{ ohms}$$

Then we can use two Amperex 8918 tubes operated in push-pull, approximately, as indicated

Plate Voltage	E = 10 kV
Grid Bias	VB = -175 V
Standing Feed	Ip = 22.8
Grid Signal	VG = 310 V per tube
Output	Vp = 8000 V "
Input Power	Wi = ~228 kW "
Output Power	W ≅ ~ 80 kW "

The tube is sufficiently described by the relation:

$$Ip = 8.21\ 10^{-5}(V_{pk} + 32.7\ Vg_k)^{1.5} \qquad (6\text{-}1)$$

and consequently the dynamic output impedance R_p of the tube is as follows:

$$R_p = \frac{353}{\sqrt[3]{I_p}} \qquad (6\text{-}2)$$

with an average value around 124 ohms and a maximum value of ~ 224 ohms.

Because the voltage step-up transforming ratio n from 16 to 50 kV is equal to 3.125 then the maximum value for the impedance transferred to the gap becomes equal to:

$$R_t = n^2(r_{t1} + r_{t2}) = n^2(101 + 176) = 2709 \text{ ohms.} \qquad (6\text{-}3)$$

and this value guarantees a good safety margin from the Robinson limit.

Now we turn back to the cavity and look for the best value of the total capacity. From Eq. (5-1) we see that the exponential factor is relevant if the transient is reduced to 1/e at least at the end of the beam pulse.

This means that we should have:

$$\frac{\tau}{2\, R_t c} = 1$$

because $\tau = (1/4)\nu$, where ν is the resonant frequency, we conclude that c should be less than:

$$C_o = \frac{1}{8\nu R_t} = 9.97 \text{ picofarad}$$

this limit is too low for a physically realizable cavity and, on the other hand, would lead to a very high value for the voltage drop ΔV.

Because the minimum value for c is always greater then ~ 100 pF then we can ignore the contribution of the exponential term and we see that the larger the capacity the lower is the ΔV.

Let ΔV be the voltage induced by the beam. Then $\Delta I = \Delta V/R_t$ is the current that should pass through the resistive component of the gap impedance. Consequently:

$$\Delta I_t = n^2 \frac{\Delta V}{R_t} \qquad (6\text{-}4)$$

is maximum value of the current that the tube should absorb.

Ignoring, as said above, the exponential factor we can write: $\Delta V \cong I_p/\omega c$.

Indicating with C_m the minimum value for the gap capacity and with ΔI_t the maximum value of the current that can pass through the tubes, substituting the value of ΔV and solving for C_m we obtain:

$$C_m = \frac{n^2\ I_p}{\omega\ \Delta I_t\ R_t} \tag{6-5}$$

With the indicated operating conditions. Because the synchronous phase is 60° off peaks then the maximum value of the injected current is reached when unperturbed conditions, the current is near 18 A in the tube that is offering the larger value of the output impedance. Consequently an acceptable value for ΔI_p could be equal to 10 A. (Because 8.1 A is the minimum value allowed for the current through the tubes.)

Substituting in (6-5) and in (5-1) we obtain:

$$C_m = 358 \text{ pf.}$$
$$\Delta V = 2782 \text{ volt}$$

and the relative value of the instantaneous voltage drop remains less than 6 per cent.

It should be noted that in this exercise we used a rather euristic method for performing the nonlinear transient analysis and the results can only indicate the order of magnitude of the various quantities. A much more accurate analysis can be performed only with the computer.

7) REMARKS -

A single ended amplifier could advantageously replace the push pull because with a single ended amplifier the beam cannot turn the tube off unless some very unrealistic conditions are verified. Moreover the control of the output impedance is easier but the problem of neutralization becomes very hard and consequently a grounded cathode single ended amplifier seems not very advisable. (The ground grid cannot be used due to its high output impedance.)

7. THE SIMPLIFIED MODEL

A simplified diagram of the monogap tapped cavity is as shown on Fig. (7-1)

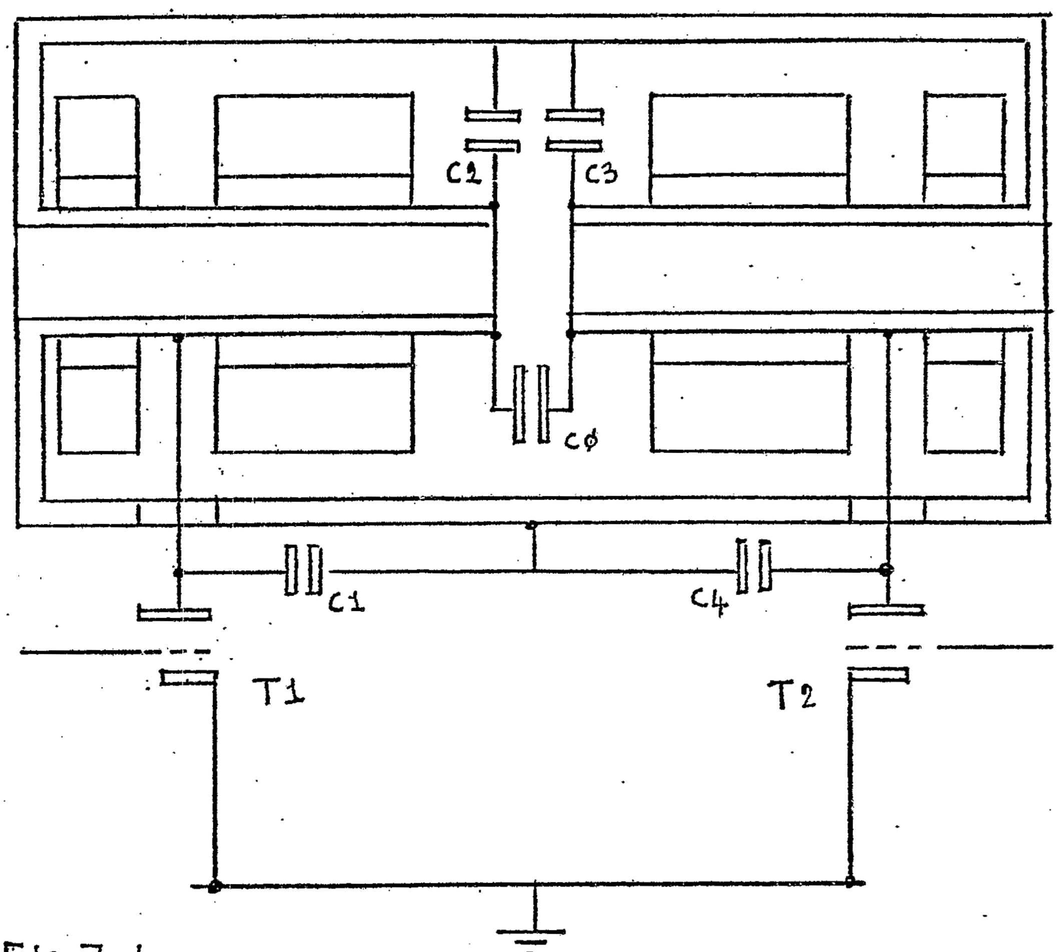

FIG. 7-1

where the capacitors indicate physical capacitors that are to be connected to the cavity as shown.

The equivalent electrical scheme is shown in Fig. (7-2).

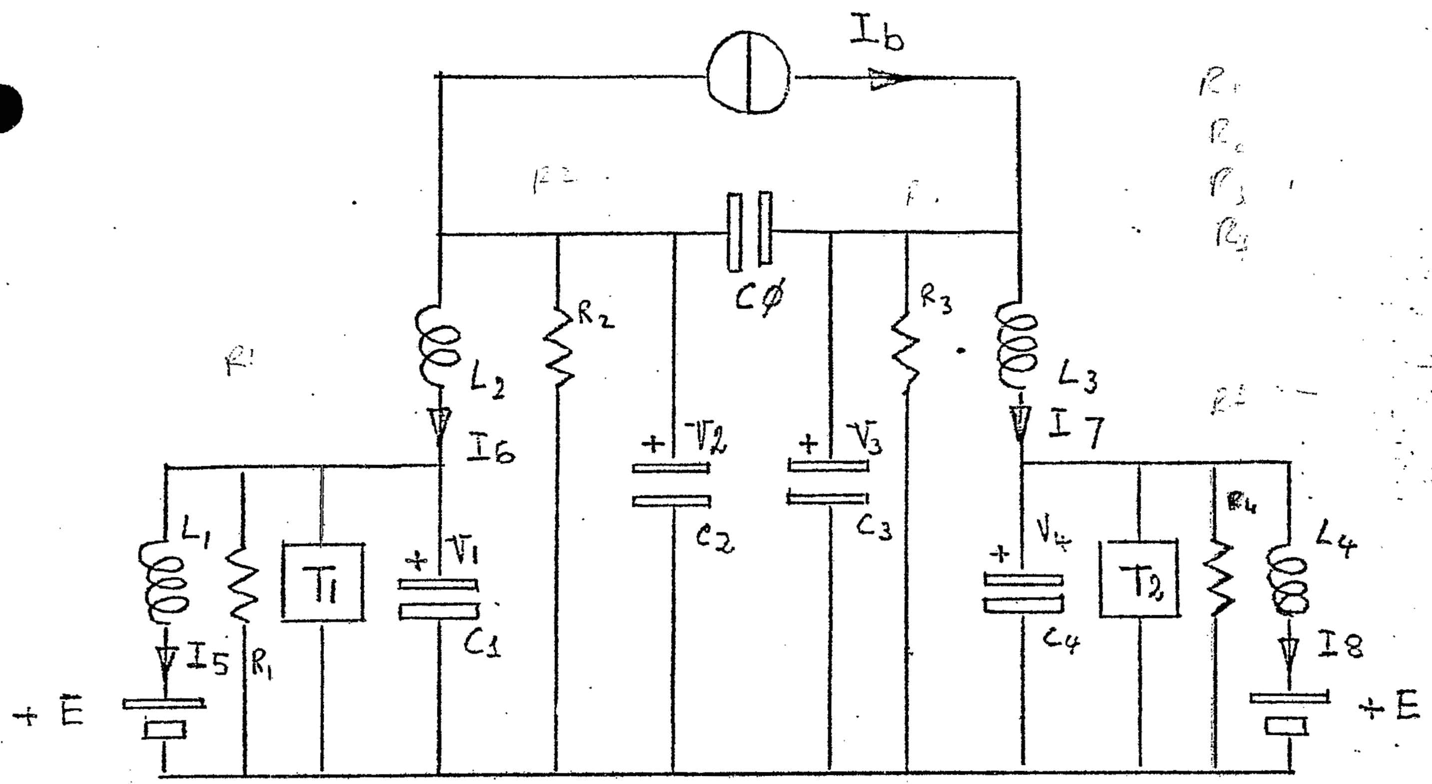

FIG 7-2

where T1 and T2 indicates the two driving tubes.

With an accuracy better than ten per cent the current in a triode is given by the following formula:

$$I_p = k\ (V_{pk} + \mu V_{gk})^{\alpha} \qquad (7\text{-}1)$$

where V_{pk} and V_{gk} are respectively the plate to cathode and grid to cathode voltages.

The constant K, μ and α depends upon the tube. For two AMPEREX tubes the above constants are as follows:

AMPEREX 8918	AMPEREX 8752
$k = 8.21\ 10^{-5}$	$k = 6.4\ 10^{-5}$
$\mu = 32.72$	$\mu = 33.8$
$\alpha = 1.5$	$\alpha = 1.5$

the AMPEREX 8918 has a plate dissipation equal to 300 kW while the AMPEREX 8752 has plate dissipation equal to 100 kW. (The tube AMPEREX 8752 is the one actually used on the present AGS rf system.)

For reasons of symmetry we should have $C1 = C_4$, $C2 = C_3$, $L1 = L_4$, $L2 = L_3$, $R1 = R_4$, $R2 = R_3$, $T1 = T_2$. Moreover, because the system should be "normally" tuned then the following condition should hold:

$$1 - \omega^2 L_1 C_1 - \omega^2 (2C0 + C2) \left[L_2 (1 - \omega^2 L_1 C_1) + L1 \right] = 0 \qquad (7\text{-}2)$$

the normal procedure is to assign the quantities C0, L_1, C_1, L_2 and to find C2 (trimming cap) accordingly with Eq. (7-2).

Because the tubes are not connected to the gap then the gap voltage should be larger than the one which is developed across the plates.

A very simple calculation shows that the limit for this transforming ratio is equal to:

$$n = \frac{1}{1 - \omega^2 (C2 + 2C0) L_2} \qquad (7\text{-}3)$$

Taking into account the previous consideration a possible set of parameters could be as follows:

Fo = 4 MHz
C0 = 400 pF
C1 = 200 pF
C2 = 56 pF
L1 = 0.6 10^{-6} H
L2 = 1.2 10^{-6} H
R1 = 6 kΩ
R2 = 15 kΩ
n = 2.84

This means that if we make the DC plate voltage equal to 10 - 12 kV then with 16 kV of plate-to-plate voltage the total gap voltage could be equal to ~ 45 kV.

The state variable equations are as follows:

$$I_5 + \frac{V_1}{R_1} + IT1 + C1\,\mathring{V}_1 = I_6$$

$$I_6 + \frac{V_2}{R_2} + C2\,\mathring{V}_2 + CO(\mathring{V}_2 - \mathring{V}_3) + I_b = 0$$

$$I_7 + \frac{V_3}{R_3} + C3\,\mathring{V}_3 - CO(\mathring{V}_2 - \mathring{V}_3) - I_b = 0$$

$$I_8 + \frac{V_4}{R_4} + IT2 + C_4\mathring{V}_4 = I_7$$

$$E + L_1\mathring{I}_5 = V1$$

$$V1 + L_2\mathring{I}_6 = V2$$

$$V_4 + L_3\mathring{I}_7 = V3$$

$$E + L_4\mathring{I}_8 = V4$$

Where IT_1 and IT_2 are the currents drawn by the tubes and E is the dc bias voltage. (It should be noted that on making $L2 \rightarrow 0$ then the tubes are directly connected to gap.)