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The RF system for the Booster: Conceptual Design

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THE RF SYSTEM FOR THE BOOSTER:
CONCEPTUAL DESIGN

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I. INTRODUCTION

The RF system for the Booster requires the design and the construction of three separate sub systems: two for heavy ion acceleration and one for proton acceleration.

The proton system requires a high output power capability and a low output impedance. The heavy ion systems require tuning over a broad frequency range.

Nevertheless, the similaries between the systems points to a common philosophy that could lead to a single model useful, "mutatis mutandis", for designing the three systems.

II. THE RF SYSTEM SPECIFICATIONS

The most stringent specifications come from the acceleration of the protons and can be summarized as follows:

Injection Energy	0.2 GeV
Ejection Energy	1.5 GeV
Number of Particle per Pulse	3×10^{13}
Maximum Number of Proton RF Stations	2
Harmonic Number	3
Frequency Range	2.5 - 4.1 MH_Z
Peak RF Voltage	90 KV
Maximum Total Ring Gap Impedance	24 KΩ
Acceleration Time	53.7 MS.
Max Power to the Beam	160 KW

III. THE ACCELERATING STRUCTURE

First of all we recognize that the RF system should be capable of accelerating 3×10^{13} protons per pulse. Because the revolution frequency will reach 1.37 MH_z then it follows that the maximum average current, Iave, is equal to 6.58 amps.

The frequency of the accelerating voltage ranges from 2.5 to 4.1 MH_z (3^{rd} harmonic of the revolution frequency). If we assume that the beam has a sinusoidal distribtuion, then:

$$I\,(t) = I_o \sin(2\pi f t),\ 0 \leqq t \leqq {}^{T}\!/_{2}$$

$$I(t) = 0, {}^{T}\!/_{2} \leqq t \leqq T$$

and

$$\frac{1}{T} \int_{o}^{T/2} I(t)\,dt = Iave$$

$$\frac{I_o}{\pi} = Iave$$

and the first harmonic of the beam current is:

$$I_1 = \frac{I_o}{2} = 1.57\ Iave$$

$$I_1 = 10.3 \text{ amperes}$$

Now we make the hypothesis that for each accelerating gap there is a cavity and its own power amplifier (single ended or push-pull).

Because class "A" operation is mandatory for preserving the output impedance then it follows that the tube (tubes) requires a standing feed at least equal to the amplitude of the first harmonic times the transforming ratio from the gap to the plate RF voltage. In our case if we tentatively assume 45 kV per gap and 12 kV per tube (that is 45 KV for a cavity with one gap and two tubes) it turns out the the minimum standing feed for each tube should not be less than $\frac{45}{24} \times 10.3 = 19.3A$.

This current requires high power tubes with a plate dissipation near 300 KW. (This is because if we assume V_p = 12kV for the plate RF voltage then the DC power supply E_b should be: $E_b = \frac{V_p}{0.7} \cong 17$ kV and $19.3 \times 17 \times 10^3 = 328$ KW is the "quiescent input power" that, for safe operation, demands the above indicated plate dissipation.

If we now make the hypothesis of paralleling the gaps two by two (as required by a two gap cavity design) then the current per tube should be increased by a factor of two and we are forced to design a huge RF system for a useful power that, on the average, remains below 200 KW.

From the point of view of the construction, the two gap cavity offers certain advantages because the bias current for the ferrite can flow along the wall of the cavity. The monogap solution requires a "crossed" loop for biasing the ferrite and balancing the RF voltage.

On the other hand it should be observed that the monogap cavity can readily be designed to be opened for inspection and maintenance. This feature is not practical with the two gap cavity.

Taking into account all the previous considerations it is clear that while both the cavities represent a solution for an RF system, the two gap cavity is complicated and very expensive, both in the construction and in operation and is not a practical solution.

Consequently the monogap cavity is suggested as the best option.

IV. THE GROUNDED GRID AMPLIFIER

The schematic, the equivalent circuit and the steady state equilibrium equations for a grounded grid amplifier are given in Fig. (1). I is the test current generator for calculating the output impedance Z_{out}. With a very simple calculation we obtain:

$$Z_{out} = r_p + R_K (1+ \mu)$$

This, normally, turns out to be very large.

As it is well known the plate current of a triode can be written as follows:

$$I_p = k (V_p + \mu V_g)^{\alpha}$$

Where V_p and V_g are the plate and grid voltages measured with respect to the cathode. Because the plate impedance rp is defined as $1/\partial I_p/\partial V_p$ we obtain:

$$r_p = \alpha k^{\frac{1}{\alpha}} I_p^{\frac{\alpha-1}{\alpha}}$$

for the tube AMPEREX 8918 we can assume: $K = 8.21\text{x}10^{-5}$, $\mu = 32.7$, $\alpha = 1.5$ and we obtain $r_p \cong 353/ \sqrt[3]{I_p}$.

The push-pull configuration introduces a factor of two because the tubes are in series. Another factor of $(1.87)^2$ comes from the transforming ratio; taking into account that the cathode resistor can be made as low as 30 Ω the amplifier can transfer on the gap an equivalent resistance equal to 8.248 kΩ.

The above figure, based on a very simple model for the tube, is rather optimistic.

A more accurate analysis made on the tube characteristics shows that a total impedance of ~ 10 kΩ can be expected.

Using two cavities and two amplifiers the total impedance along the machine remains below 20 kΩ and this is consistent with the specifications. It should be noted further that the ferrite losses will further reduce the effective impedance.

V. THE CAVITY-AMPLIFIER SYSTEM

Fig. 2 shows the scheme for the cavity-amplifier system where Co represents the decoupling capacitors and the voltage step up transformer is obtained by tapping the ferrite at the appropriate locations.

From another point of view it would be an important electro mechanical simplification if the decoupling capacitor Co could be used also as part of the step up network. The scheme would appear as shown in Fig. 3.

However, it should be taken into account that with this solution the transforming ratio depends upon the tuning of the cavity.

This may represent a real drawback if the tuning of the cavity is to be adjusted in order to compensate for the beam quadrature component.

For this reason the first solution seems more conservative though it is more complicated, mechanically.

VI. AMPLIFIER AND CAVITY PARAMETERS

A possible candidate for the cavity ferrite is the ferrite ring shown in Fig. 4. It is attractive because its inner radius is large (0.15 m). If this ring is used, the clearance between the inner radius of the ring and the outer radius of the beam tube is equal to ~ 0.075 meters. Since it is not advisable to exceed electric field gradients of 5 kV/cm it follows that the voltage between the beam tube and the ferrite cooling plates (washers) should not exceed 37.5 kV.

Fortunately, with a single symmetric gap design the RF gap voltage is divided between the two cavity sections and it follows that a total voltage of about 75 kV per gap could be safely used.

Since the total design voltage is equal to 90 kV two cavities are needed and it seems reasonable to allow 45 kV per cavity.

In this way we gain a large safety factor for the voltage gradients in each cavity and the introduction of a ferrite biasing loop should present little difficulty.

The next step is to determine the ferrite core and the R/Q ratio.

With a heavily loaded cavity, as it is our case, the ratio R/Q is nearly equal to $\frac{1}{\omega_o C_{eq}}$ where ω_o is the resonant radian frequency of the cavity and C_{eq} is its total equivalent capacity.

A large valve for C_{eq} reduces the value of the transient voltage induced by the beam but increases the current in the cavity and the required magnetic permeability of the ferrite decreases accordingly thus mandating larger bias currents.

Following the above criteria we can design our cavity and the calculations will be done using several simplifying hypothesis.

We assume that the ferrite fills inter conductor space and we start calculating a dummy cavity whose radii are equal to the radii of the ferrite ring.

As it is well known, there are two important conditions:

(1) The total voltage should be obtained without exceeding the B_{max} of the ferrite.

(2) The RF current should be able to produce the desired B_{max} assuming that the law of Biot and Savart is applicable. So we should have

$$\int_{R_1}^{R_2} B_{max} \frac{R_1}{r} \ell_F \, d\, r = \frac{V}{\omega}$$

where ℓ_f = length of ferrite

μ_r = relative permeability

V = gap voltage

R_1, R_2 as defined in Fig. 2

then

$$\omega C V \frac{\mu_o \mu r}{2\pi R_1} = B_{max}$$

where we assumed, as is the case, that $R/Q \cong \frac{1}{\omega C}$.
For the low frequency end we obtain:

$$\ell_f = \frac{V/2\pi f}{R_1 \; B_{max} \, \ell n \left(\frac{R_2}{R_1}\right)} = 1.055 \text{ m}$$

$$C\mu_r = \frac{B_{max} R_1}{f V \mu_o} = 3.76\text{x}10^{-8} \text{ Farads.}$$

Now a reasonable value for C, in order to minimize the transient beam loading, could be around 400 pf and it follows that our μ_r should be ~99.166.

It is easy to check that the cavity is tuned:

$$(2\pi f)^2 \times \frac{\mu_o \mu r}{2\pi} \ \ell_f \ \ell n \frac{R_2}{R_1} \times C_{eq} = 1$$

Using the calculated ferrite length in a practical cavity gives:

Ferrite Length	42x0.025	= 1.05 m
Washers Length	44x0.03	= 0.132
Gap Length	45/5	= 0.09 m
Gap Flanges Length	2x 0.03	= 0.06 m
End Section Length	2x 0.1	= 0.2 m
Clearance for Tapping	4x 0.05	= 0.20 m
Clearance Around the Gap	2x 0.05	= 0.10 m

This gives a total cavity length: ℓ_{cav} = 1.8 m.

At this point we are ready to take into account the air annuli between the ferrite rings and cavity walls. Let R_3 and R_4 be the inner and the outer radii of the cavity respectively. Then the total inductance L_T is:

$$LT = \frac{\mu_o \ \ell \ cav}{2\pi} \quad \frac{R_4}{R_3} + \frac{\mu_o}{2\pi} (\mu \ - 1) \ \ell_F \ \ell n \frac{R_2}{R_1}$$

Because the total voltage depends upon B we substitute for ℓ_f and obtain:

$$L_T = \Upsilon + \frac{\mu_o \mu_r}{2\pi} \times \frac{V}{R_1 B \omega}$$

where $\Upsilon = \frac{\mu_o}{2\pi}\left(\ell n \frac{R_4}{R_3} - \ell_F \; \ell n \frac{R_2}{R_1}\right)$

Taking into account the tuning condition $\omega^2 L_T C_T = 1$ we obtain:

$$\omega^2 C_T \Upsilon + \frac{\mu_o \mu \; \omega C_T V}{2\pi R_1 B} = 1$$

Now because $\omega^2 C_T \Upsilon > 0$ then it follows that we should have:

$$\frac{\mu_o \mu \; \omega C_T V}{2\pi R_1 B} = 1 - \varepsilon \tag{1}$$

where ε is a small quantity namely $\varepsilon = \omega^2 c \Upsilon$ and we obtain $C = C_T$.

Substituting C_T into equation (1) the value of μ is determined.

It should be observed that the above calculations are valid if the mechanical size of the cavity is very much smaller then the free space wavelength of the fields and $\omega^2 C \Upsilon << 1$.

AMPLIFIER OPERATING CONDITIONS:

Now we will calculate the operating conditions for the final amplifier which is operated grounded grid push-pull.

The schematic diagram, the equivalent circuit and the equilibrium equations for a grounded grid single ended amplifier are given in Fig. 5 and the conclusions are easily extended to the push-pull case.

We take the driving voltage V_s with zero (reference)phase and we assume:

$$V_p = V_o\, e^{j\Psi};\ I = I_b e^{j\phi}$$

to indicate the plate voltage and the beam current. Solving we obtain:

$$V_p = \left[\frac{V_s}{R_k}\left(\frac{1}{r_p} + G_m\right) + I\left(\frac{1}{r_p} + \frac{1}{R_k} + G_m\right)\right] \Big/ \left[\frac{1}{r_p R_k} + Y\left(\frac{1}{r_p} + \frac{1}{R_k} + G_m\right)\right]$$

Where $Y = G + jB_s$ is the load admittance.

It is easy to show that if $B_s = 0$, $I = 0$, and $r_p \cong \infty$ the plate voltage reduces to the familiar formula for the gain of an ordinary grounded grid amplifier.

If the amplifier has to see a tuned (resistive load) then Ψ must be equal to zero and from the previous expression we obtain:

$$B_s = \frac{I_b \sin\phi}{V_o}$$

and the current I_A that the amplifier should supply for the real part of the load current and which is composed of the in phase beam current and the cavity resistive component is:

$$I_a \cong -\,(GV_o - I_b \cos\phi)$$

where the minus sign indicates that the amplifier must supply the current toward the node. Moreover, because the beam is to be accelerated then it follows that $0 \leqq \phi \leqq \pi/2$.

Now the total cavity shunt impedance R_s is estimated to be 20KΩ while the peak value of the real component of the first harmonic of the beam current is approximately 10.3A. The peak power delivered to the beam is nearly 160 KW at a total ring voltage of ~ 90 kV].

Taking into account the voltage transformation from the gap to the tubes

$n = \frac{45}{24} = 1.875$ we obtain that the first harmonic I_a of the tube current:

$$I_a = \left(\frac{V_{GAP}}{R_s} + I_b COS\phi\right) n = 20.4 \text{ AMP.}$$

In order to guarantee class "A" operation the quiscent current should be at least equal to this value. [17 kV DC plate voltage. - 400 V DC grid bias; 347 KW Plate input power; 160 KW output power and an overall efficiency near 23%].

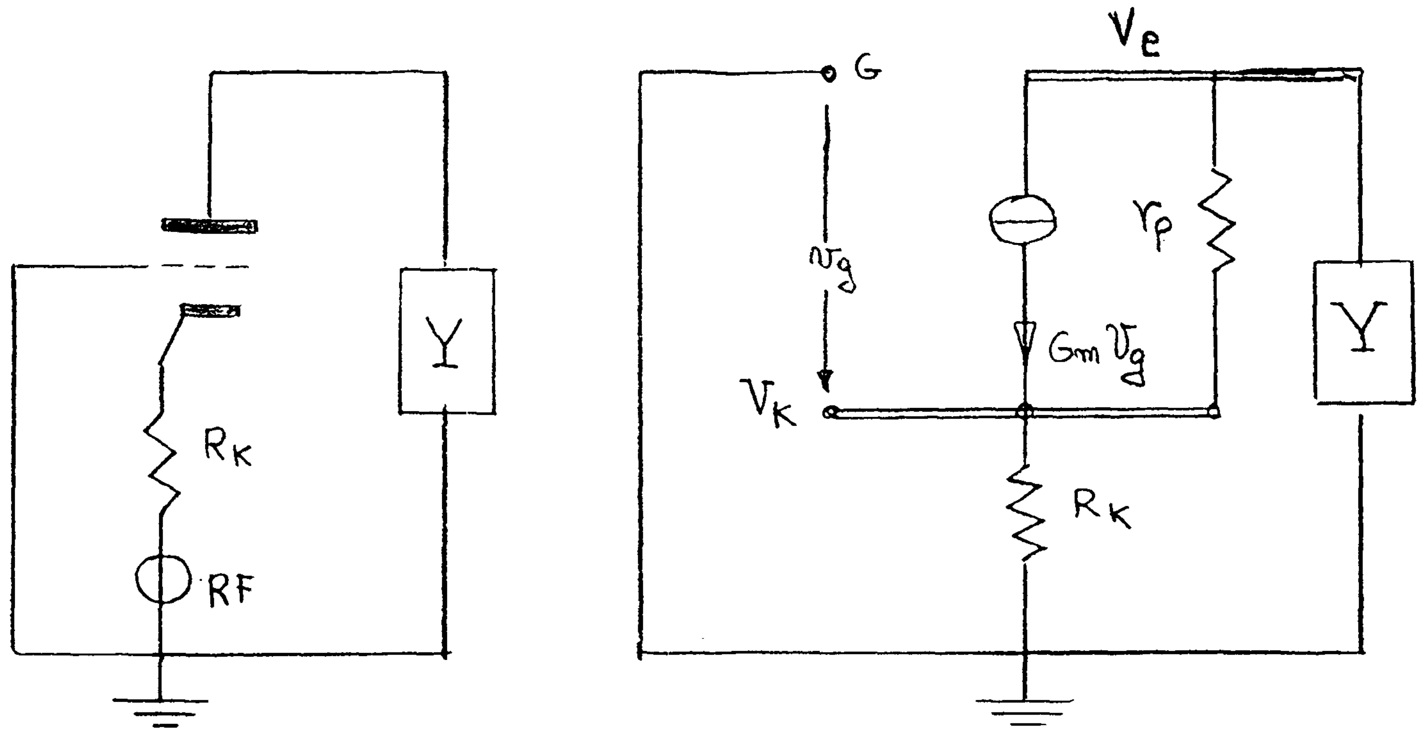
The load line is shown in Figure 6 on the 8918 constant current characteristics.

Obviously, for two tubes the total input power should be equal to ~ 694 KW. It seems important to recognize that such heavy conditions are to be expected at the end of the cycle and that will last only one - two milliseconds.

This means that the tubes are to be large in order to withstand the most severe load conditions but on the average the input power should be much less.

From another point of view is the demand of "current handling capability". That points toward powerful tubes and this sets the limits for the quiescent current. A plate modulated system would help very much in saving power.

In any case, the amperex 8918 trhiode is worth considering.



$$V_g = -V_K$$

$$\begin{cases} \left(Y + \dfrac{1}{r_p}\right) V_e - \left(\dfrac{1}{r_p} + G_m\right) V_K = I \\[2ex] -\dfrac{1}{r_p} V_p + \left(\dfrac{1}{r_p} + \dfrac{1}{R_K} + G_m\right) V_K = 0 \end{cases}$$

$$V_p = \frac{r_p + R_K(1+\mu)}{1 + Y\left[r_p + (1+\mu)R_K\right]} I$$

FIGURE 1

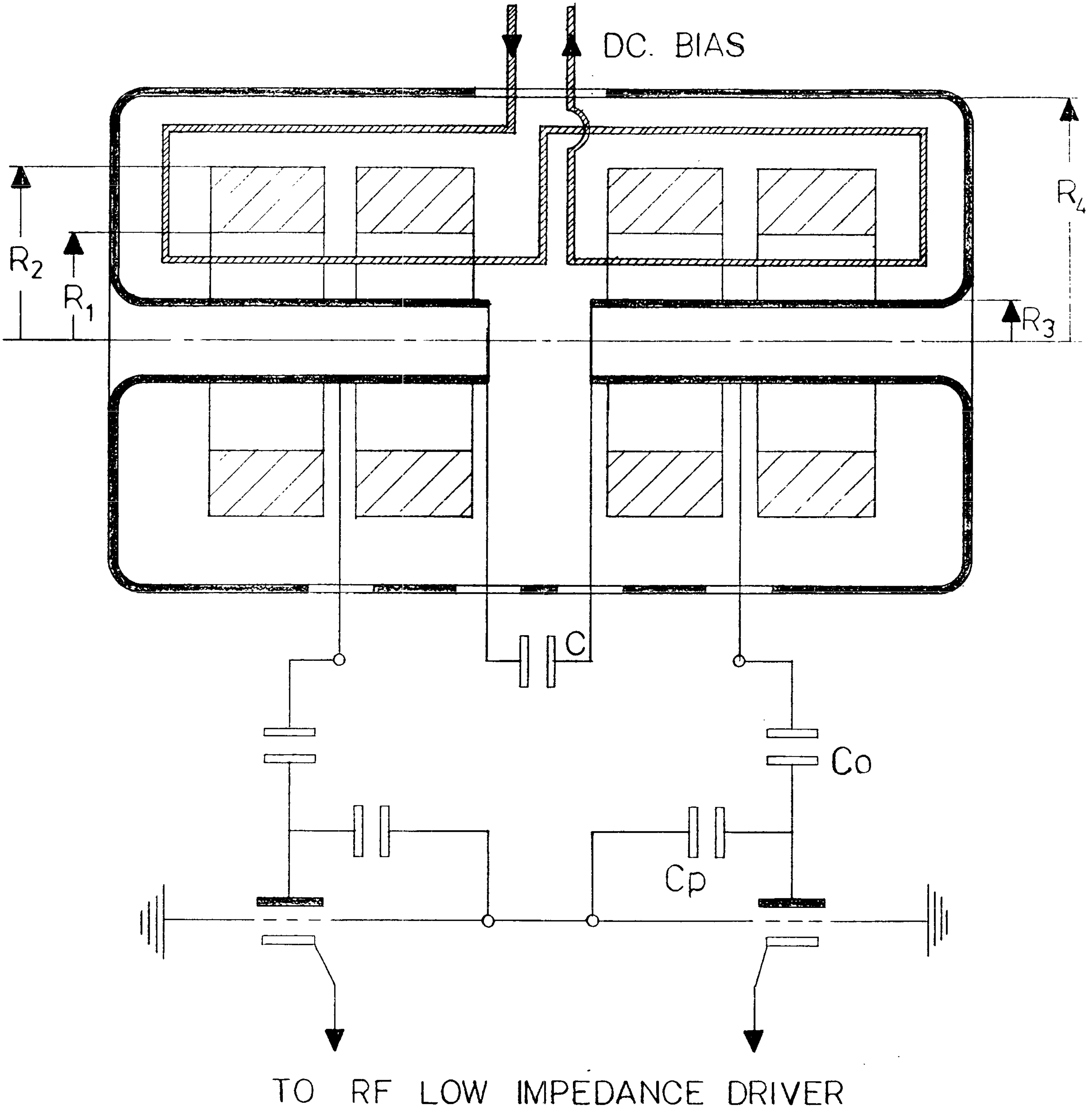


FIGURE 2

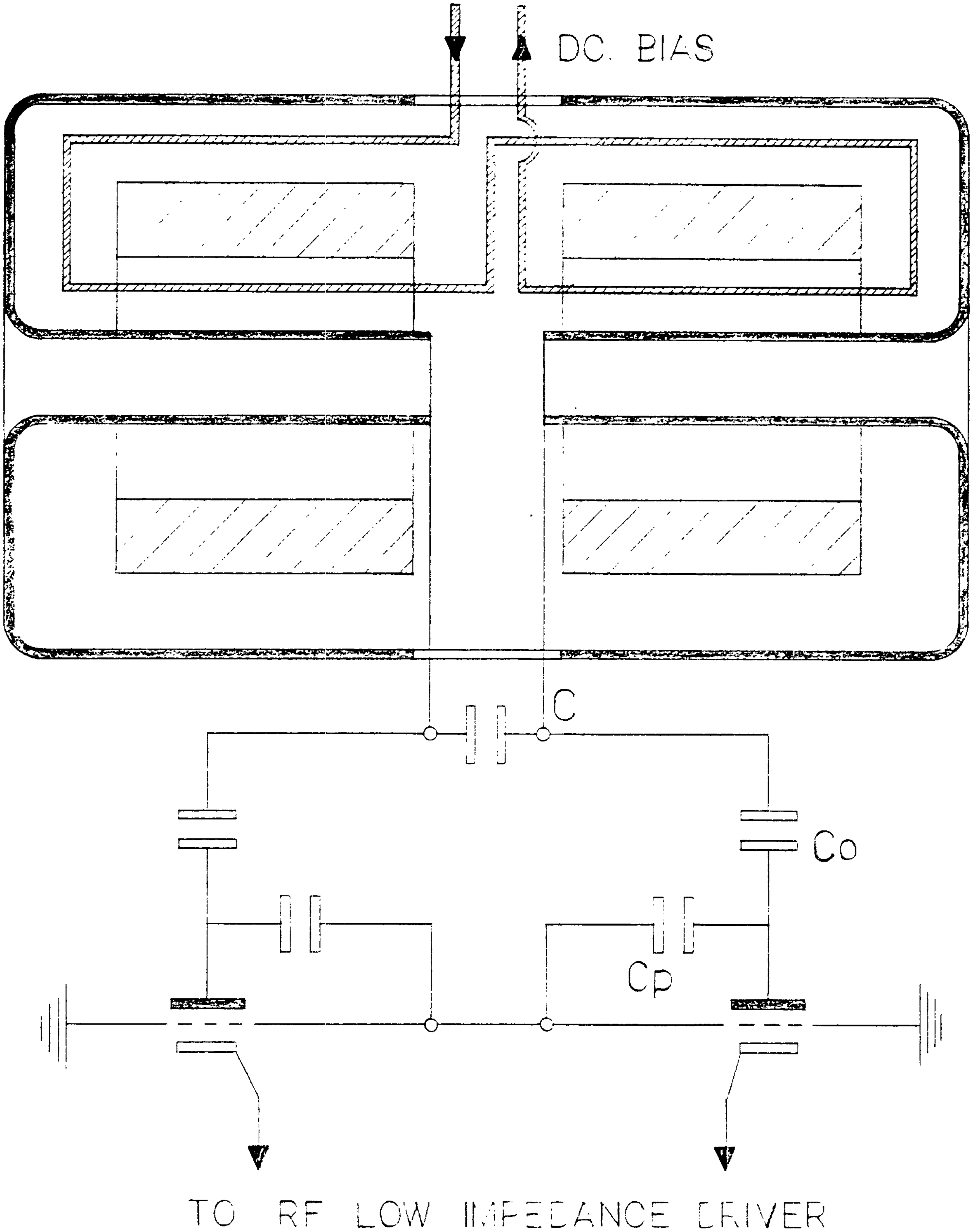
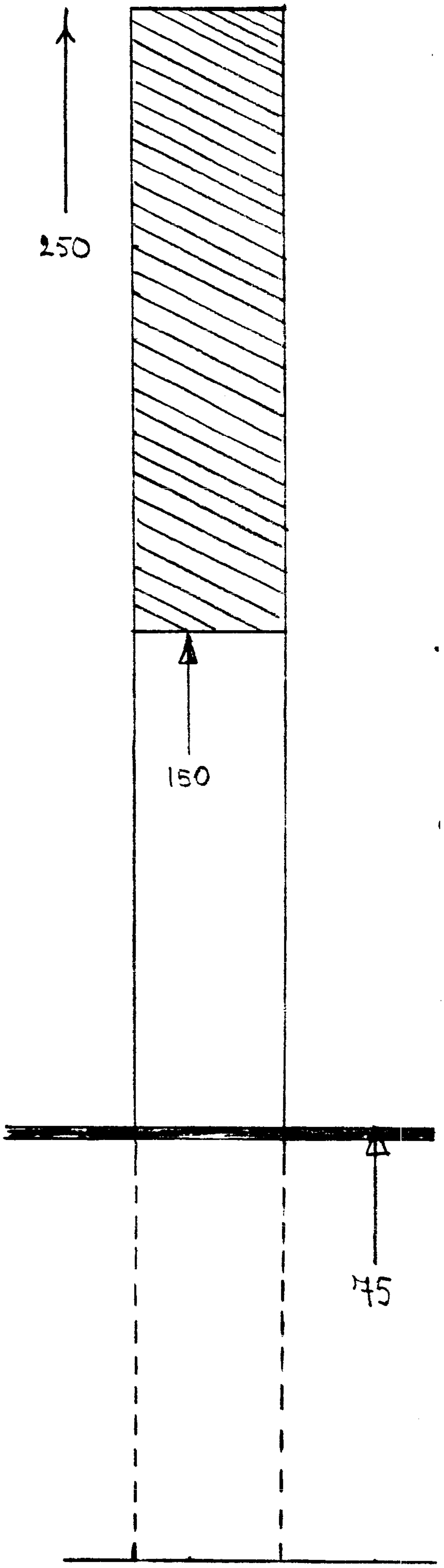


FIGURE 3



FERRITE RINGS

FERRITE MN 8CX

$B_{MAX} = 0.0355$ WEBER/m^2

POWER LOSS 0.35 W/CC

$R_2 = 0.25$, $R_1 = 0.15$, $T = 0.025$

$V_R = 1.067$ KV/RING

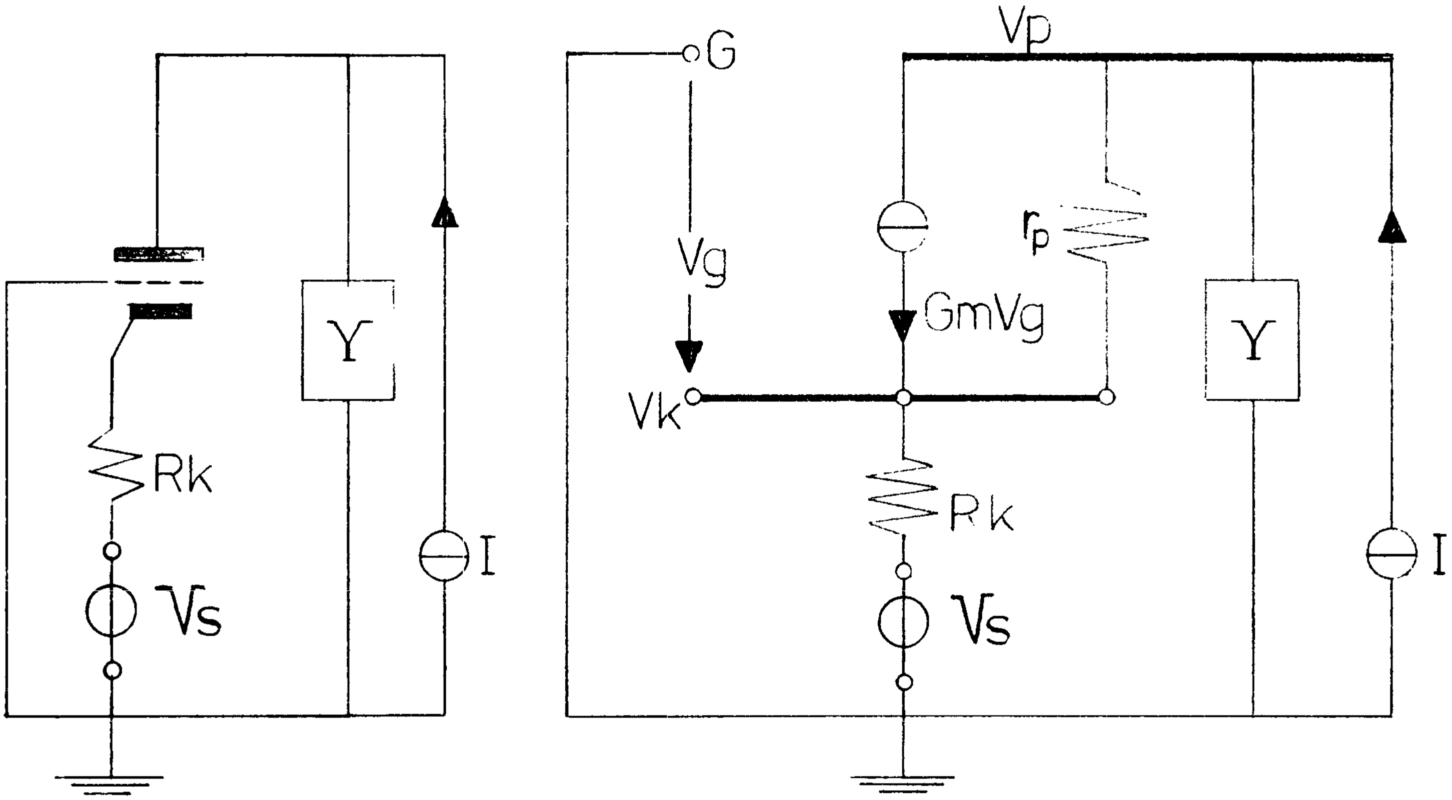
$W_R = 1.1$ KW/RING

$N \cong 42$

$W = 46.2$ KW

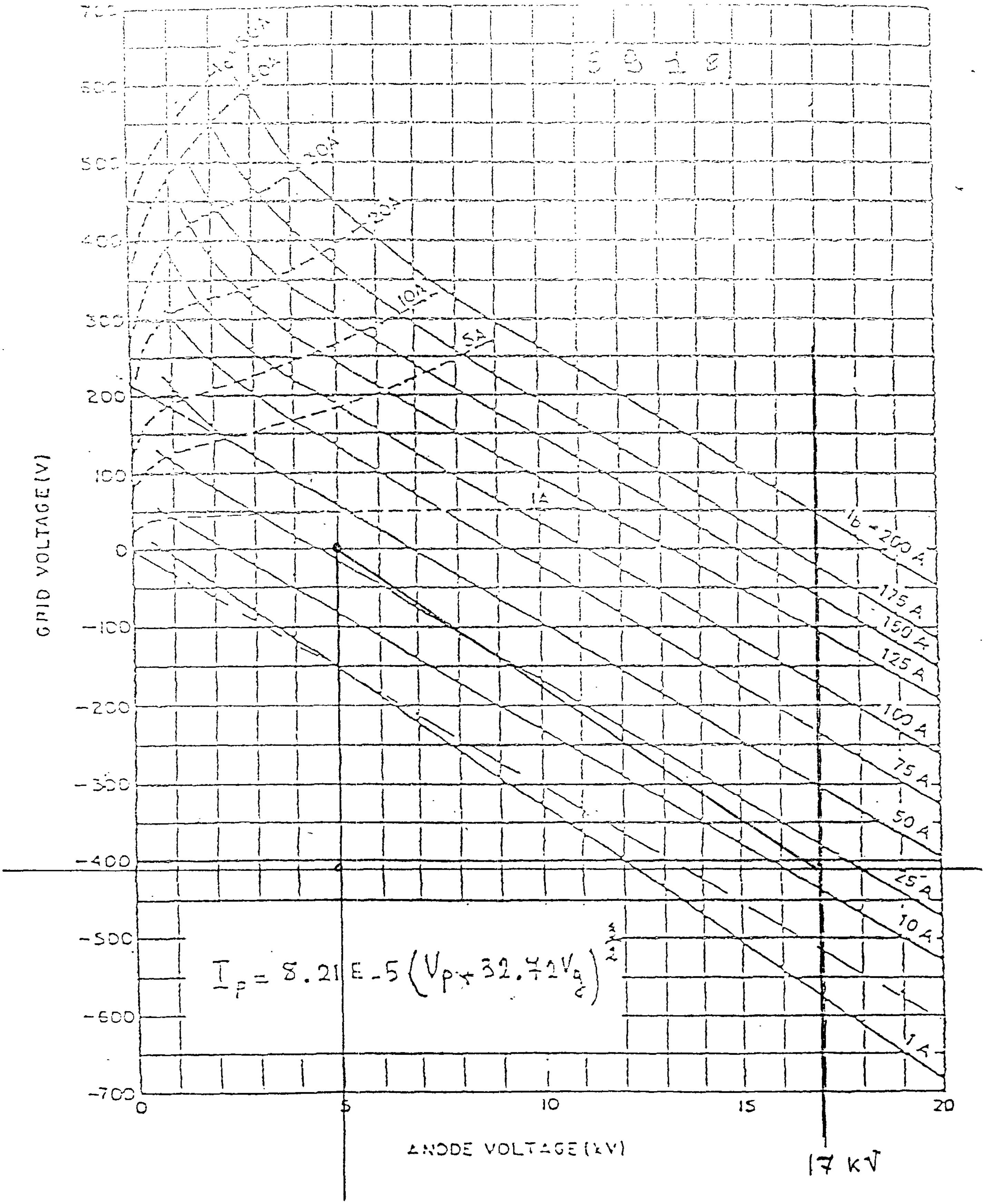
$R_{eq} = 22$ KΩ

FIGURE 4



$$\begin{cases} \left(Y + \dfrac{1}{r_p}\right) V_p \;-\; \dfrac{1}{r_p} V_K = I - G_m V_g \\ -\dfrac{1}{r_p} V_p + \left(\dfrac{1}{r_p} + \dfrac{1}{R_K}\right) V_K = \dfrac{V_s}{R_K} + G_m V_g \\ V_g = - V_K \end{cases}$$

FIGURE 5



GRID VOLTAGE (V)
ANODE VOLTAGE (kV)
17 kV
$I_p = 8.21E{-5}\left(V_p + 32.72V_g\right)^{3/2}$
I_b = 200 A
175 A
150 A
125 A
100 A
75 A
50 A
25 A
10 A
1 A

FIGURE 6