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PUSH PULL OPERATION THE RF CAVITY

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INTRODUCTION

The RF cavity is intrinsically capable of operating in a push pull mode whether the drive current is single ended or balanced (i.e. push pull). The push pull operation of the cavity is due to the tight RF coupling provided by a figure-of-eight winding looped through the two halves of each cavity. This winding can also be employed as a bias-winding. This note is not concerned with the figure-of-eight winding functioning as a bias winding, but rather is concerned with this winding functioning as an RF transformer.

At the AGS the bias winding is considered only as a means of controlling the permeability of the ferrite. Push-pull operation of the cavity is achieved by transformer coupling a balanced signal into the cavity. In previous technical notes concerning the Booster RF system, the cavity is excited by two drivers operating in a push-pull mode[1]. A literature search reveals that the CERN PS Booster is driven by a single tube operating class B. Tight RF coupling and push pull operation of the cavity is achieved by two figure-of-eight bias windings.[2] It is probably advantageous to use the present AGS scheme to bias the ferrite and add an independent figure-of-eight winding for RF coupling.

RF CAVITY

Consider the elementary RF cavity given in Figure 1. The cavity is excited by two vacuum tubes providing RF drive currents i_1 and i_2. There is no special relationship between the currents i_1 and i_2. In fact, one of these currents can be of zero value. The individual RF tube current (i_1 or i_2) divides equally between the beam-pipe and the B+ lead. An induced RF current i_x circulates in the bias winding.

Since the bias winding is shorted to RF and does not contain voltage sources, the net flux in the loop is zero. Therefore, the net H- field around the loop is zero. In terms of currents.

$$(i_1 + i_x) + (i_2 + i_x) = 0 \tag{1}$$

A positive sign connects the individual terms, due to the fact that the current sense and windings direction are opposite in the two halves of the winding. Therefore,

$$i_x = \left(\frac{i_1 + i_2}{2}\right) \tag{2}$$

$$i_1 + i_x = \frac{i_1 - i_2}{2} \tag{3}$$

$$i_2 + i_x = -\left(\frac{i_1 - i_2}{2}\right) \tag{4}$$

ELECTRICAL ANALYSIS

An electrical equivalent circuit of the cavity is given in Figure 2. In this figure L is the self-inductance of each half of the cavity, M is the mutual inductance between each half of the bias winding and cavity, C is the gap capacitance, and R represents all the losses of the cavity.

From Figure 2 the following relationships hold between the voltages v_1, v_2, and v. The gap voltage is representative by v, v_1 and v_2 are the feed voltages to ground.

$$v_1 = -L\frac{di}{d_t} - M\frac{dix}{dt} - LC\frac{d^2v}{dt^2} - \frac{L}{R}\frac{dv}{dt} \tag{5}$$

$$v_2 = -L\frac{di2}{dt} - M\frac{dix}{dt} + LC\frac{d^2v}{dt^2} + \frac{L}{R}\frac{dv}{dt} \tag{6}$$

Due to the tight coupling L ≈ M. Also using (3) and (4) in (5) and (6)

$$v_1 = -L\frac{d}{dt}\left(\frac{i_1 - i_2}{2}\right) - LC\frac{d^2v}{dt^2} - \frac{L}{R}\frac{dv}{dt} \tag{7}$$

$$v_2 = L\frac{d}{dt}\left(\frac{i_1 - i_2}{2}\right) + LC\frac{d^2v}{dt^2} + \frac{L}{R}\frac{dv}{dt} \tag{8}$$

Solving for v

$$v = v_1 - v_2 \tag{9}$$

$$v = 2L \frac{d}{dt} \left(\frac{i_1 - i_2}{2}\right) - 2LC \frac{d^2v}{dt^2} - 2\frac{L}{R} \frac{dv}{dt} \tag{10}$$

If $v(t) = V \cos \omega t$, then (10) becomes

$$V \cos \omega t = - L \frac{d}{dt} (i_1 - i_2) + 2\omega^2 LCV \cos \omega t - \frac{2L}{R} \frac{dv}{dt}$$

Since the cavity is tuned to resonant with the source frequency

$$2\omega^2 LC = 1,$$

therefore,

$$-L \frac{d}{dt} (i_1 - i_2) - \frac{2L}{R} \frac{dv}{dt} = 0$$

and

$$v(t) = \frac{R}{2} (i_2 - i_1) \tag{11}$$

To observe the intrinsic push-pull mode of the cavity, note from (7) and (8) that

$$v_1 = -v_2 \tag{12}$$

independent of the values of i_1 and i_2. Even with a single driver tube and either i_1 or i_2 of zero value, $v_1 = -v_2$.

CLASS B DRIVEN

For the case in which two tubes are employed and operated class B push-pull.

$$L_1 = A_o + A_1 \cos \omega t + A_2 \cos 2\omega t - A_4 \cos 4\omega t$$

$$L_2 = A_o - A_1 \cos \omega t + A_2 \cos 2\omega t - A_4 \cos 4\omega t$$

The fourier coefficients for the class B current waveform are related to the peak value of the current pulse D of each tube.

$$A_0 = \frac{D}{\pi}$$

$$A_1 = D/2$$

$$A_2 = \frac{2}{3\pi} D$$

$$A_4 = \frac{2}{15\pi} D$$

Since the drive currents are push-pull only the fundamental components of current contributers to the gap voltage v. All the even harmonics cancel, characteristics of a symmetrical push-pull circuit.

Therefore, expression (11) becomes

$$v(t) = - RA_1 \cos \omega t$$

$$= - \frac{RD}{2} \cos \omega t$$

and the power delivered to the cavity is given by

$$P = \frac{RD^2}{8}$$

Consider a second case in which only one tube is employed and the peak value of the tube current is given by D. In this case the even harmonic terms do not cancel and contribute to the gap voltage. The analysis is modified by assuming that v(t) is described by a harmonic series.

$$v\ (t) = V \cos \omega t + \alpha \cos 2\omega t + \beta \sin 2\omega t + \ldots\ldots. \qquad (13)$$

The values of the coefficients are calculated by employing the method of undetermined coefficients.

$$v\ (t) = -\ \frac{R}{4} D \cos \omega t - \left(\frac{4}{9\pi}\right)\frac{\omega LD}{1 + \frac{16}{9}\frac{w^2L^2}{R^2}} \sin 2\omega t - \frac{16}{27\pi}\,\frac{\left(\frac{\omega^2 L}{R^2}\right)}{1 + \left(\frac{16}{9}\right)\frac{w^2L^2}{R^2}} RD \cos 2\omega t \qquad (14)$$

with R>ωL the above expression reduces to

$$v(t) = \sim \frac{R}{4} D \cos \omega t \ - \frac{2}{9\pi}\ \frac{1}{wC} D \sin 2\omega t$$

in terms of the Q of the cavity

$$v(t) = -\frac{R}{4} D \ \left(\cos \omega t \ + \frac{8}{9\pi Q} \sin 2\omega t\right) \qquad (15)$$

For the Booster the beam loaded Q of the cavity is 13.5 and the gap voltage will contain a maximum of 2.1% second harmonic distortion. The fourth harmonic distortion is less than 0.2%.

It is interesting to note that with a single-drive tube, the cavity is driven push-pull but does not result in the cancellation of even harmonic terms. The push-pull condition requires that:

$$v_1(t) = -v_2(t)$$

and is imposed by the figure-of-eight winding.

If in addition:

$$v_2(t) = v_1(t-T/2)$$

where T is the period of the excitation

then the gap voltage would be free of all even harmonic distortion terms and contain only odd harmonic terms; for class B operation, only the fundamental. The latter condition can be achieved with two identical tubes, excited push-pull.

LOAD LINE

An examination of the equilibrium equations of the cavity (11) and (12) permits an interpretation of the cavity as a 2:1 step-up auto transformer.

$$v(t) = \tfrac{1}{2} R\,[i_2 - i_1] \qquad (11)$$

$$v(t) = 2v_1 = -2v_2 \qquad (12)$$

where R is equivalent load resistance across the gap. For balanced operation

$$i_1 - i_2 = 2A_1 \cos \omega t = D \cos \omega t \qquad (16A)$$

$$v_1(t) = -\frac{RD}{4} \cos \omega t \qquad (17A)$$

Therefore, the locus of operation for each tube, or loosely speaking the "load line" for class B operation of a tuned load, defined as the locus of the peak plate current D as a function of the peak plate voltage, is a line with a slope of $-4/R$.

If the cavity is driven from a single tube then the expression for $(i_1 - i_2)$ and $v_1(t)$ are modified as

$$i_1 - i_2 = A_1 \cos \omega t = \frac{D}{2} \cos \omega t \tag{16B}$$

$$v_1(t) = -\frac{RD}{8} \cos \omega t \tag{17B}$$

and the locus of operation is a line with slope of $-8/R$.

Figure 3 gives the load line of a tube, if the cavity is driven by either two tubes or one tube. The plate supply voltage is E_{bb}.

For either case the maximum idealized possible load power is

$$\frac{2E_{bb}^2}{R}$$

and the corresponding power supply drain is

$$\frac{8}{\pi} \frac{E_{bb}^2}{R}$$

The maximum conversion efficiency is

$$\frac{\pi}{4} \text{ or } 78.5\%$$

Thus a given cavity can be driven push-pull, energized to a given power level by either a one tube or a two tube driver. Obviously the plate current and plate dissipation capabilities of the single tube must be twice that of each tube in the two tube driver.

SIMULATION

The operation of the proton cavity with a single tube operating class B has also been studied through computer simulation, employing the current analysis program SPICE. The cavity configuration and component values are given in Figure 4. The drive current is a half-wave sinusoid adjusted to give a peak gap voltage of 17.5 Kv. Figure 5A shows the exciting current i(f gen1), gap voltage (v_2-v_1) and figure of eight winding current i(l1sec) to a common time scale.

Figure 5B shows the cavity circulating current i(l1) and gap voltage to a common time scale.

REFERENCES

1. M. Puglisi, A. Massarotti, The RF System For the Booster: Conceptual Design, Booster Tech. Note 64, Sept. 26, 1986.

2. U. Bigliani, et al. The RF System for the CERN PS Booster, NS-18, June 3, 1971.

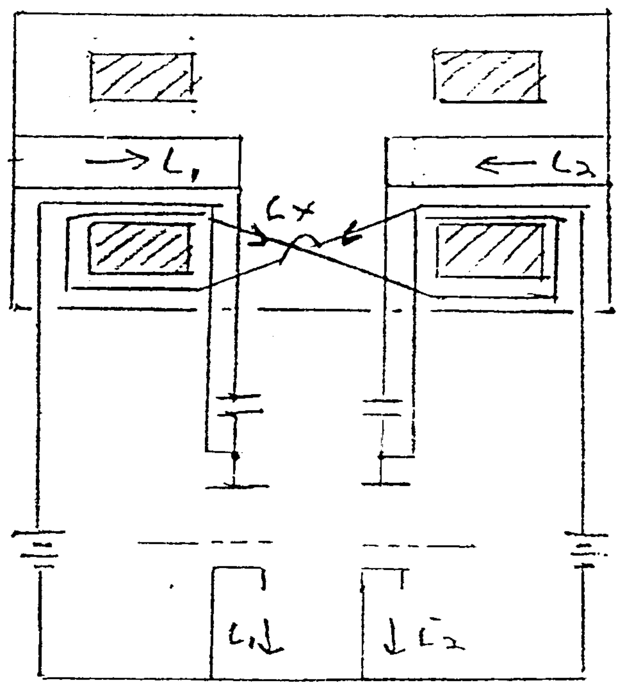


Figure 1
ELEMENTARY RF CAVITY
WITH BIAS WINDING

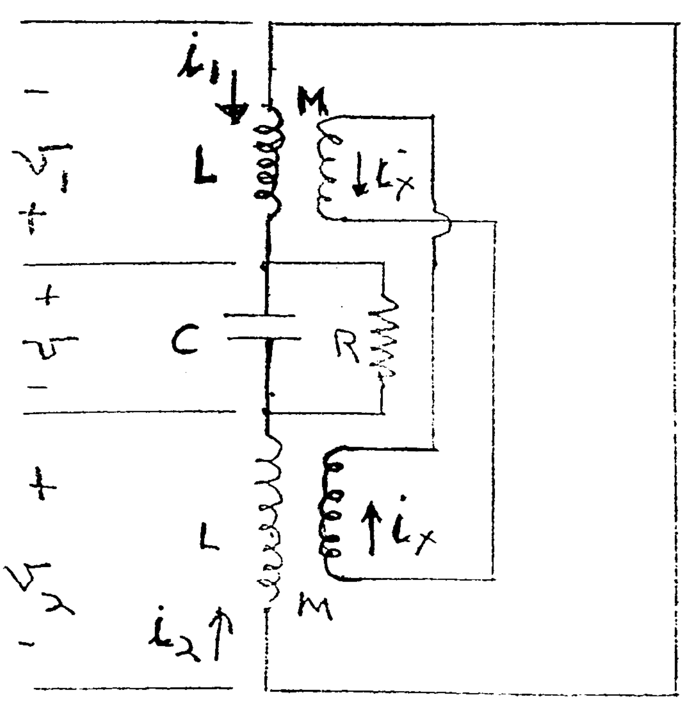


FIGURE 2
ELECTRICAL
EQUIVALENT
CIRCUIT
OF THE CAVITY

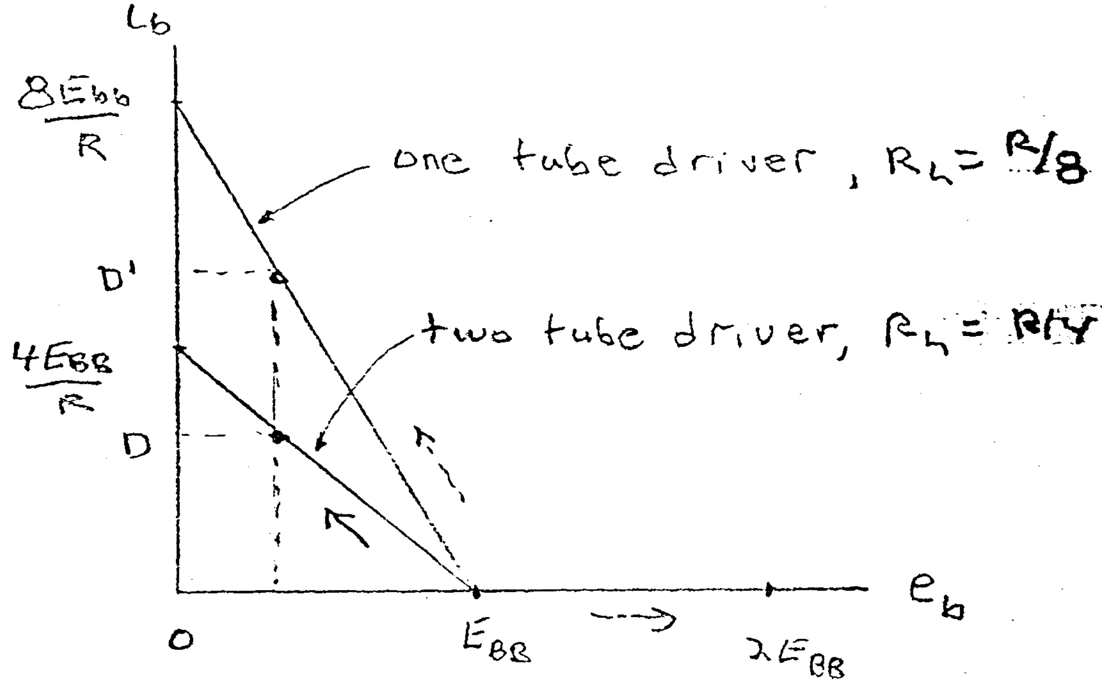
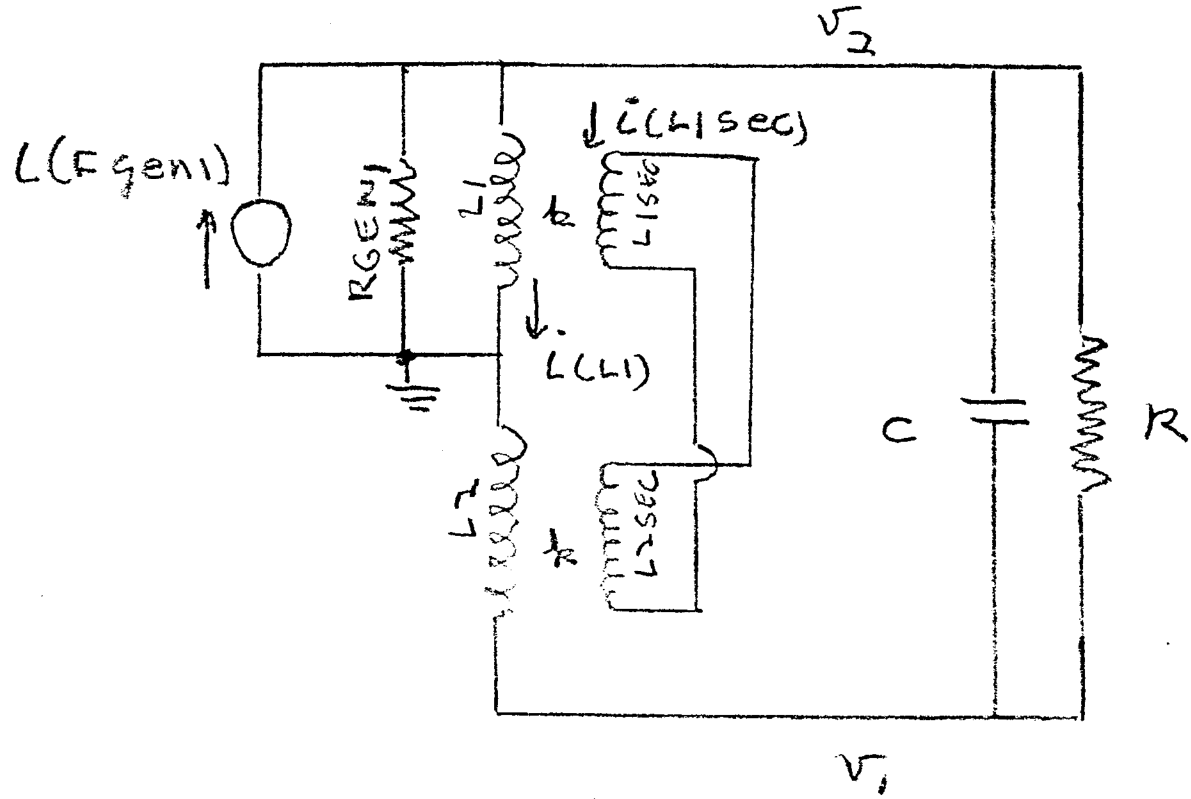


Figure 3

Locus of Operation of Class B Driver



Source Frequency = 4.2 Mhz.

L1 = L2 = 1.1433 μH

L1SEC = L2SEC = 1.1433 μH

$k_1 = k_2 =$ 0.9999

C = 628 $\mu\mu$F

R = 2.58 KΩ

RGEN1 = 4.25 KΩ

Fig 4
MODEL OF CAVITY USED FOR COMPUTER STUDY

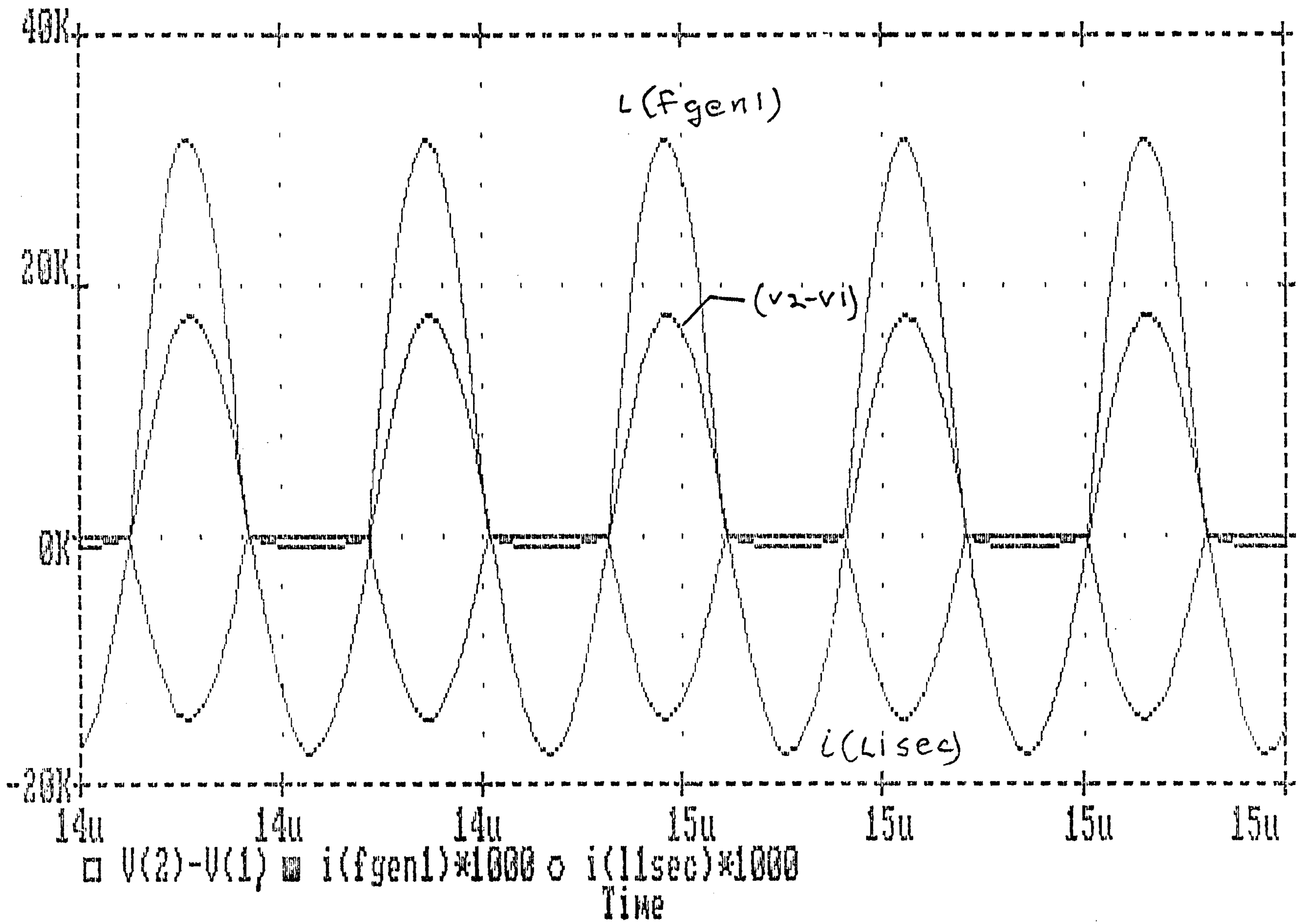
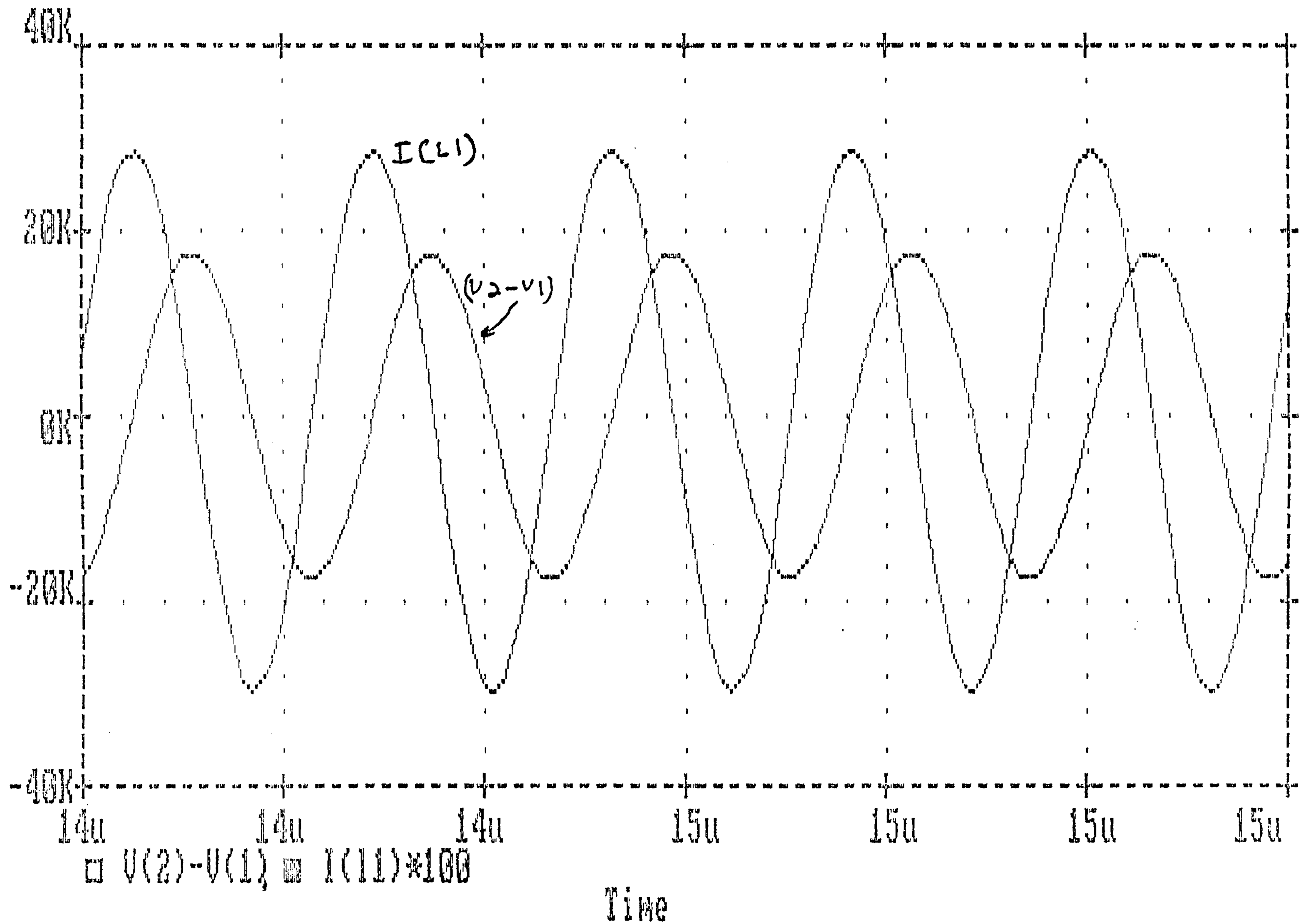


Figure 5B
computer Generated Cavity Waveforms



Enter a variable or expression: I(11)*100

Figure 5B

COMPUTER-GENERATED CAVITY WAVEFORMS