OPERATION CHARACTERISTICS OF THE CARMATRON TUBE

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Among the numerous types of travelling-wave tube which have been studied during the last few years, those of the Carmatron family have an interesting field of application when a simple power generator which can be tuned electronically over a rather narrow bandwidth (5–10%) is required.

The general structure of the Carmatron is similar to that of the cylindrical magnetron, but the circuit is open and is terminated by two coaxial feeders; the power flows out through one (according to the direction of the magnetic field), while the other is matched and absorbs power only in the event of a mismatch at the main output. The interaction between the circuit and the beam is similar to that of the M-type carcinotron, which means that synchronism is achieved between the rotating beam and a backward wave; but the fact that the modulated beam into the interaction space returns after one revolution has two results: the valve oscillates with a much shorter line than the M-type carcinotron and the range of electronic tuning is reduced because the re-entrancy of the beam introduces a new phase condition.

Fig. 1.—Experimental Carmatron.

Fig. 1 shows the valve which was tested; it includes an interdigital line with 19 fingers, and its cathode comprises 16 filaments of pure tungsten, which avoids troubles due to back-heating. Its main dimensions are as follows:

Anode radius	6 cm
Cathode radius	4 cm
Filament diameter	0·02 cm
Finger length	9 cm
Pitch of the interdigital line	1·6 cm
Gap width (between adjacent fingers) ..	0·8 cm
Finger height	0·6 cm
Inner angle between the two outputs ..	70°

We shall indicate first typical operational characteristics of such a valve, and then explain the observed phenomena by a comparison with the well-known magnetron, the M-type carcinotron and the voltage-tunable magnetron.

Operation Characteristics of the Carmatron

Since both ends of the tube are matched by two external loads, we can impose a magnetic field, B, and a direct voltage, V, between the cathode and the circuit; there is then a large r.f. power, P, in one of the loads and a much smaller power in the other (less than 10% of P) at an angular frequency ω and with a direct current I; for a given magnetic field, increasing the voltage causes rapid increases in r.f. power and current; the frequency also increases by a few per cent, but above a particular voltage the power and the current suddenly fall to very low values and the frequency jumps to a very different value. This behaviour is repeated as the voltage is raised, and with the tube tested it was possible to obtain three such modes of oscillation.

If different magnetic fields are used the curves shown in Fig. 2 are obtained, which indicate that the power and efficiency are increasing with the magnetic field: for this mode one obtains a frequency range of 5% and for magnetic fields greater than those indicated, efficiencies of 70% and powers of 2·6 kW. Before the tests it was hoped to control the direct current, and consequently the r.f. power, by the cathode heating; in practice, if we decrease the cathode heating the efficiency falls rapidly even before the current begins to decrease, without any clear reason.

These features, which have been but briefly reported, can be better understood by reference to the magnetron, the M-carcinotron and the voltage-tunable magnetron, taking into account the new factor peculiar to the Carmatron, namely the phase shift between the free beam and circuit waves which occurs when the frequency varies.

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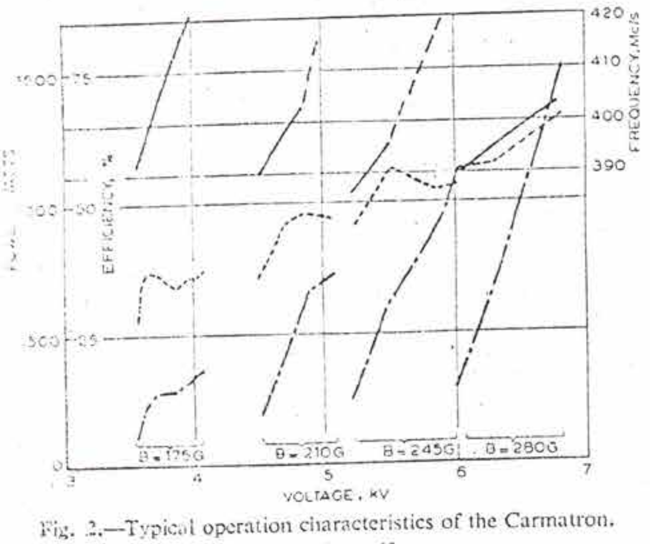

Fig. 2.—Typical operation characteristics of the Carmatron.
Mode number = 10.
——— Frequency.
– – – – Efficiency.
—·— Power.

Comparison with the Magnetron

The classical theory of the magnetron[1] shows that, if one neglects the r.f. phenomena, the anode current appears only if $V_r > B_r^2$, where V_r and B_r are the reduced voltage and magnetic field given by

$$V_r = \frac{V}{\frac{1}{2e/m}\omega_0^2 r_a^2}$$

$$B_r = \frac{B}{\frac{2}{e/m}\omega_0 \frac{1}{1-(r_c/r_a)^2}}$$

where r_a and r_c are the anode and cathode radii, ω_0 is the rotation velocity of the r.f. wave, and $e/m = 1 \cdot 76 \times 10^{11}$ in M.K.S. units.

Moreover, after Hartree, oscillations can occur only when $V_r > 2B_r - 1$, so that the useful range of V_r is, in fact, given by $2B_r - 1 < V_r < B_r^2$. The variation of starting voltage with magnetic field for the mode already described is shown in Fig. 3; it is lower than the Hartree line would indicate and nearer the curve marked 'synchronism' (the supposition in this case being that oscillation takes place when synchronism occurs between the outer layers of the Brillouin-flow beam and the travelling wave); in fact, it depends slightly on the coupling impedance, R, of the structure, which is defined for a travelling wave by

$$R = \frac{EE^*}{2\gamma^2 P}$$

where E and E^* are respectively the r.f. field and its conjugate at the anode radius, and γ is the propagation coefficient. This fact is easy to observe if we provide a reflection at the output, which is, at a fixed frequency, nearly equivalent to an increase of the coupling impedance.

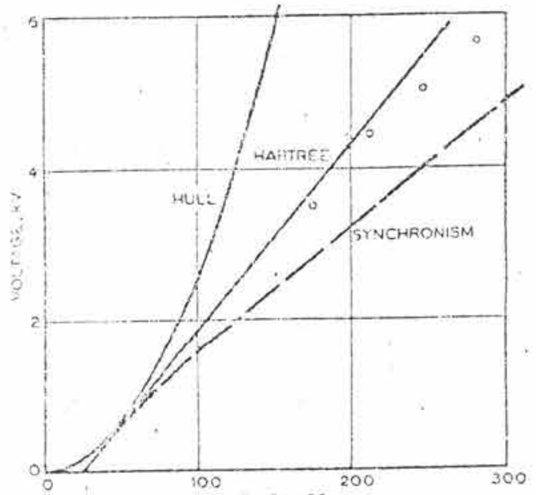

Fig. 3.—Theoretical starting voltage and experimental values (shown by the circles).

On the other hand, the electronic efficiency, η, is lower than $1 - 1/V_r$, and the general increase of efficiency with the magnetic field could be explained by this simple expression. But it is proved by experiments that the electronic efficiency depends on the r.f. field and increases with it; one can consider that at low fields a part of the potential space-charge energy is converted by r.f. spontaneous movements into unorganized kinetic energy which heat the anode uselessly when such electrons arrive on it. This is shown to be true in the magnetron, and in a very striking way in the M-type carcinotron, where the efficiency is nearly proportional to the coupling impedance from 10 to 60%.

Comparison with the M-Type Carcinotron

As in the case of the carcinotron, it is easy to measure by cold tests the wavelength in the circuit as a function of the free wavelength. This curve is shown in Fig. 4 and corresponds to the

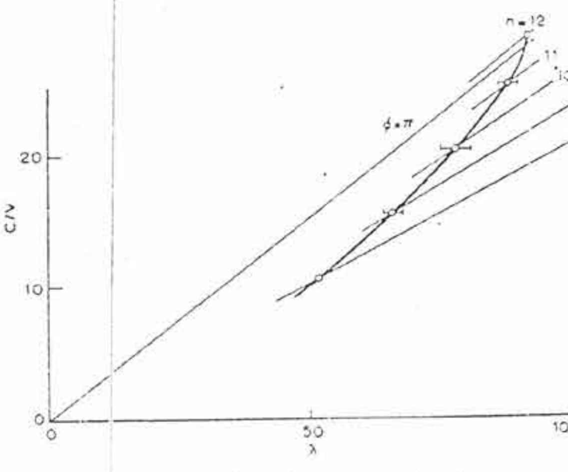

Fig. 4.—Dispersion curve and modes.
○○○ Theoretical points of oscillation.
|—| Practical band.
n = Number of wavelengths.

classical backward-wave propagation of the interdigital line; but in the Carmatron the beam modulation comes back into phase shift between adjacent cells, corresponding to integral numbers of delayed wavelength along the perimeter of the valve; these points are marked on the dispersion curve by circles and the practical frequencies observed are located around them.

It may seem surprising that the Carmatron has a high efficiency and low electronic tuning bandwidth, whereas the voltage-tunable magnetron, heavily loaded, has a low efficiency (less than 10%) but a large electronic tuning bandwidth (an octave), because if the Carmatron is reduced to two cells only, one obtains a tube which is very similar to the voltage-tunable magnetron: in order to understand this, it is necessary to consider the energy equilibrium in the valve.

Comparison with the Voltage-Tunable Magnetron

In general, oscillation occurs when the load admittance is equal to the electronic admittance in magnitude but opposite in sign, so far as these admittances can be defined. The load admittance is usually linear and dependent only on the angular frequency ω: in the magnetron[2] one supposes that the electronic admittance does not depend on ω but only on the r.f. field, but this hypothesis is not valid for either the voltage-tunable magnetron or the Carmatron.

The voltage-tunable magnetron, as studied by Boyd,[4] comprises a waveguide capacitively loaded by two combs constituting an interdigital squirrel-cage structure, a cylindrical cathode being mounted along its axis; it is shown schematically in Fig. 5(a)

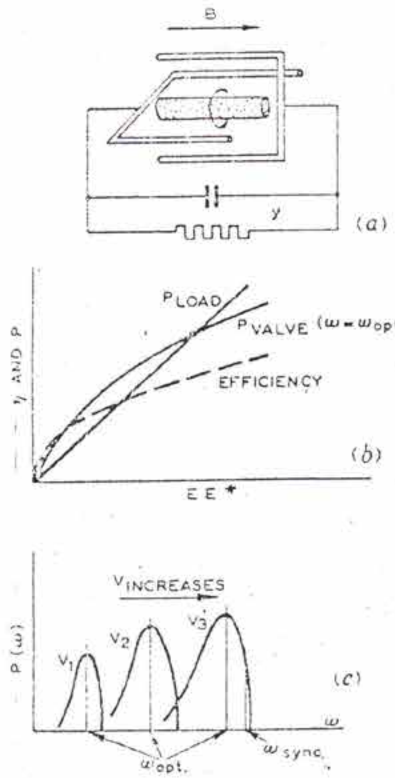

Fig. 5.—The interdigital voltage-tunable magnetron.

(a) Schematic.
(b) Operating point of the valve.
(c) Reduction factor due to the deviation of the wave velocity from the d.c. beam velocity.

with an admittance, Y, including the capacitance between the two combs. If the susceptance of this capacitance is negligible in comparison with the conductance of the load, the load admittance is independent of the frequency; on the other hand, for a given direct voltage and r.f. field, the r.f. current induced by the beam in the circuit increases rapidly when the angular frequency, ω, is varied, so that synchronism is realized between the wave and a part of the rotating beam. The optimum value of ω is obviously proportional to V/B, and we can consider for a qualitative discussion that P is the product of two functions, namely a function of the r.f. level EE^* only [Fig. 5(b)] and a function of $\omega/(V/B)$ only [Fig 5(c)]; then, the power, P, in the load being proportional to EE^* in a way known by cold tests, the operating point is easily found.

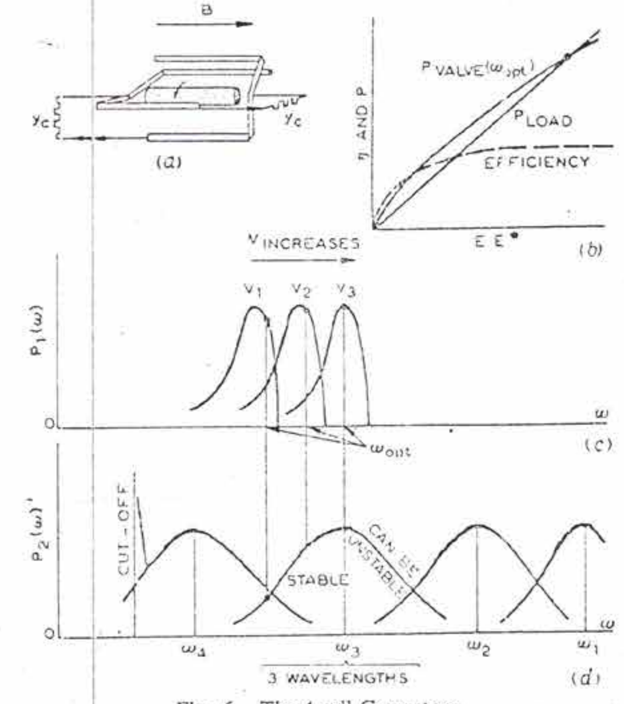

Fig. 6.—The 4-cell Carmatron.

(a) Schematic.
(b) Operating point of the valve.
(c) Reduction factor due to the deviation of the wave velocity from the d.c. beam velocity.
(d) Reduction factor occurring when the number of wavelengths is not an integer.

In the Carmatron, shown schematically in Fig. 6(a), another kind of dependence of P on ω appears, because the free-beam and circuit wavelengths are the same only for a discrete set of angular frequencies, ω_m, which do not depend on the direct voltage V (Fig. 4); for lower or higher angular frequencies, P decreases because the beam modulation does not return in phase with the r.f. field. Consequently, one can assume that P is now the product of three functions, namely EE^* (E being measured at the output), $\omega/(V/B)$ and $(\omega - \omega_m)/\omega_m$ which are shown in Figs. 6(b), 6(c) and 6(d).

In the Carmatron the power in the load is also proportional to EE^*, by the relation

$$P = \frac{EE^*}{2\gamma^2 R}$$

which, with the previous curves, defines the operating point. To explain the asymmetry of the curve in Fig. 2 one can remark that the variation of direct current with direct voltage also has the shape of the curves in Fig. 6(d), and that the internal impedance of the power supply can consequently cause the sudden jump from one mode to the next.

We must now discuss the role of the number of cells for the voltage-tunable magnetron and the Carmatron; these two valves are identical when there are two cells only, if the length of fingers is small compared with the wavelength and if the load conductance of the voltage-tunable magnetron is twice the matching loads of the Carmatron (because they are in parallel). From this point, an increase of the number of cells in the voltage-tunable magnetron does not change—to first approximation—the efficiency or the bandwidth if the load conductance is proportionately increased; but when the load conductance decreases one can see from Fig. 5(b) that the r.f. field, and consequently the efficiency, are increased. The role of the capacitance between the coat's is then more important, and it reduces the electronic bandwidth. In the Carmatron, on the other hand, an increase in the number of cells involves an increase in the interaction space, and thus of the r.f. power, whereas the coupling impedance and the corresponding straight line in Fig. 6(*b*) remain constant: the maximum efficiency is then increased; but, at the same time, the curves in Fig. 6(*d*) become sharper and the electronic bandwidth decreases. It may be added that the Platinotron,[5] which has a structure very similar to that of the Carmatron, operates only when it is locked by an external driver—which is not the case for the Carmatron; it is probable that the coupling impedance of the Platinotron is lower than that of the Carmatron.

We have described the most typical features of the Carmatron, but this picture is rather coarse, and further experimental data will be required before one can assess the relative merits of Carmatron and a voltage-tunable magnetron for partic applications.

REFERENCES

(1) SLATER, J. C.: 'Microwave Electronics' (Van Nostrand, 19

(2) COLLINS, G. B.: 'Microwave Magnetrons', M.I.T. Radia Laboratory Series, Vol. 6 (McGraw-Hill, 1948), p. 28

(3) WARNECKE, R. R., GUÉNARD, P., DOEHLER, O., and EPSZ B.: 'The M-Type Carcinotron Tube', *Proceedings of Institute of Radio Engineers*, 1955, 43, p. 413.

(4) BOYD, J.: 'The Mitron, an Interdigital Voltage-Tun Magnetron', *ibid.*, p. 332.

(5) BROWN, W. C.: 'Platinotrom increases Search Radar'Ra *Electronics*, 1957, 30, p. 164.

DISCUSSION ON THE ABOVE CONTRIBUTION

Dr. J. E. Rowe: One of the chief disadvantages of the type of Mitron the authors describe is that only half the power is used. In the S-band version the tube was operated across the standard S-band waveguide with tapered ridges at each end. The output was taken off at one end and the other end was terminated in a flat load, so that half the power was wasted. A later version suggested by Professor Hok at the University of Michigan permitted the recovery of the wasted power.

The same tube was operated in an elliptical cavity with the tube at one focus and the load at the other, so that the tube was fed to the load. The tube was the same as that used in the waveguide and gave 1·5–2 watts ± ½ dB from 1·9 to 3·8 Gc/s. The cavity was about the size of a normal sardine tin and ¼ in high. The efficiency was still lower in this case, being under 5%, as it was in the ridged waveguide model.

Dr. R. Dunsmuir: Why have the authors designated the cathode elements separately rather than as a continuous tube?

Secondly, can they describe the pattern of the voltage around the device when it is operating? The Carmatron is likened to the M-carcinotron, and the simple theory—so far as I understand it for the M-carcinotron—indicates that the beam modulation increases sinusoidally from zero at the cathode end to a maximum at the collector end of the tube. No power propagates in the circuit at the collector end, but the r.f. voltage rises sinusoidally to a maximum at the output connection at the gun end. However, in the Carmatron, the r.f. beam current must be continuous round the complete loop (unless there is some clever demodulation arrangement between the output and the lossy section), so that the r.f. beam-current amplitude must traverse a complete sine-wave cycle. If the circuit-voltage amplitude also passes through a complete cycle round the tube, and is zero at the lossy termination, it must also be zero at the output. Can the authors explain what really occurs?

Dr. S. W. Klüver (*United States*): How many times do the electrons rotate before they are caught on the anode?

Mr. W. E. Willshaw: I am very interested in the authors' description of the Carmatron and its characteristics, particularly by the work on this valve at the low-frequency end of the microwave spectrum. I think the real importance of a Carmatron is that it extends the principle of the voltage-tunable magnetron to much higher frequencies.

In the early work on the voltage-tunable magnetron carried out by Wilbur and Peters at relatively low frequencies, a lumped circuit was effectively paralleled across the magnetron straps, so that there was no frequency-determining circuit element. It was found that coherent oscillations occurred under certain emission conditions at a frequency proportional to the angular velocity of the rotating beam. This gave frequency coverage of the order of 2 : 1 at a fixed magnetic field by variation o voltage.

When this principle was extended to higher frequencie was done also at the University of Michigan, the resistive were achieved by placing interdigital fingers across a lo waveguide. At still higher frequencies the lumped capaci of the fingers become so significant that one is forced system in which the fingers are made part of a matched line, and this is achieved in the Carmatron. Howeve introducing a new parameter—the dispersion characteris the delay line—the tuning range is restricted as the au point out. Thus the particular significance of the Carm is for voltage-tunable operation at the highest freque especially where cathode-emission problems may limit output of the M-carcinotron.

Are any figures available for the power dissipated a cathode by electrons returning to it, expressed as a fracti the anode input power?

Mr. A. G. Stainsby: Temperature limitation, if it is nece will be a very real difficulty in this type of device. I g that the limitation here was a matter of the efficiency c valve, which fell if the valve was not operated under temper limited conditions. But is temperature limitation not necessary in this device in order to prevent a very large inc of line or anode current when the device is frequency modu Is there any sign of the 'frequency sticking' which has reported by American workers?

Mr. A. Karp (*United States*): The 'sticking-point' phenom was first observed by Hull (at the U.S. Signal Corps Engin Laboratory) when he tried to use an interdigital line in junction with a linear, continuous, emitting sole and ob that the only oscillation frequency obtained was that the π-mode cut-off of the interdigital line. He explained th resulting multi-velocity cloud could always have some within it electrons slow enough to couple to the π-mode. there represented the lowest frequency and the lowest el velocity in the band.

I later observed at Holmdel when using, not an inter structure, but one which had its π-mode cut-off at the frequency end of the band, that it was possible to voltag from below the 'sticking point', but that having reache point, further increases of line voltage produced no increase in frequency.

Because the authors' beam is effectively a univelocit their device is rather different from the linear emitti devices which Hull and I tried, so that the 'sticking question may be irrelevant in this context.

Messrs. O. Doehler, B. Epsztein and J. Arnaud (*in rep* answer to Drs. Rowe and Dunsmuir, we used a cathode built from tungsten filaments in order to avoid the back-bombardment of the cathode, which is dangerous in a continuous-wave valve.

In the Carmatron the electric field along the structure is not very different from the field in a carcinotron; it is maximum at the output and zero at the other, but the beam modulation is nowhere zero; the waves propagating along the circuit are the same as for the carcinotron, but the boundary conditions are different: the oscillation conditions are obtained if one assumes that the field at one end of the circuit is zero and that the modulation of the beam is the same at both ends of the circuit.

The radial velocity of the electrons, queried by Dr. Klüver, is given by E/B (E being the r.f. field); the time spent by an electron between the cathode and the anode can perhaps be computed, but the important fact is that the length of the delay line may be the half that of the carcinotron line with the same efficiency—which indicates a strong feedback due to the re-entrant beam.

In answer to Mr. Willshaw, the pure-tungsten filament has too poor an emission to be used at high frequencies. The concentration on low frequencies was thus due to a cathode problem; with this cathode the back-heating is negligibly low and could not be measured.

In reply to Mr. Stainsby, we observed that the efficiency fell when the valve was operated under temperature-limited conditions—which was not the case with the Mitron; consequently it has been impossible to avoid a variation of the power with voltage.

The frequency sticking described by Mr. Karp has not been observed; the distance between the two ends of the line of carcinotron must be such that the beam returns in opposite phase at the π-mode, so that the oscillations on this mode could be avoided. This condition was not realized in the valve tested; moreover, the beam would be a univelocity one only if the cathode radius were zero, which is not the case. It is then possible that it is the different structure of the cathode which permits us to avoid the sticking-point.

RESULTS OBTAINED ON CROSS-FIELD CARCINOTRONS UNDER PULSED OPERATION

By M. FAVRE.

(*Contribution presented at the* INTERNATIONAL CONVENTION ON MICROWAVE VALVES, *20th May*, 1958.)

The advantages of M-type valves for the generation and amplification of microwaves is well known. One of their main characteristics is their high efficiency, which renders them particularly useful in high-power applications. In fact, M-type carcinotron crossed-field backward-wave oscillators (Fig. 1) can

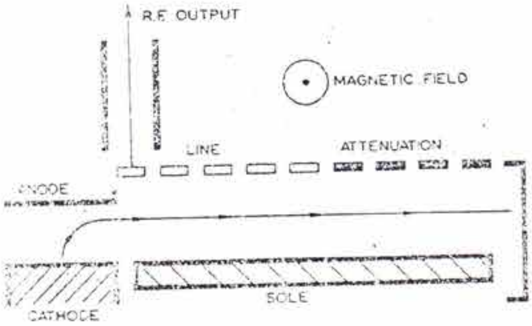

Fig. 1.—M-type carcinotron.

deliver more than 1 kW at 3 Gc/s with efficiencies as high as 45 %. This contribution shows how these advantages are retained under pulsed condition, and examines the problems that arise from this mode of operation, which has previously concerned the magnetron oscillator only. Finally, details are given of results obtained with valves operating in the S- and X-bands.

BASIC PROBLEMS

Build-Up Time.—For very short pulses there may be limitations due to the build-up time of the oscillations. This has already been calculated in the small-signal case, and is derived from

$$V = V_0 \varepsilon^{t/\tau} \varepsilon^{j\omega t}$$

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where τ, a function related to the design characteristics of the valve, is given by

$$\tau = \frac{1}{\pi}\,\frac{1}{\sqrt{\left(\frac{I}{I_a}\right)}}\,\frac{l}{c}\left(\left|\frac{c}{v_g}\right| + \left|\frac{c}{v_\phi}\right|\right)$$

From measurements made by Harman on O-type carcinotrons, where the shape of the curve of θ as a function of the current is almost identical to that found theoretically in the M-type carcinotron, we find a build-up time of the form $\theta = K\tau$, where K is of the order of 40.

If we suppose that the laws are approximately the same in M-type carcinotron, a valve operating at 3 Gc/s gives $\theta = 5 \times 10^{-8}$ sec. This may be a limitation for pulse lengths smaller than 5×10^{-7} sec.

Space Charge.—High peak currents give importance to the concept of frequency pushing, i.e. the variation of frequency with beam current. In the small-signal case the variation of the phase velocity is given by

$$\Delta\left(\frac{c}{v}\right) = \left(\frac{c}{v_\phi} + \frac{c}{v_g}\right)\frac{\Delta\lambda}{\lambda} = K\frac{I}{V_0 + |V_s|}$$

Calculations for a practical case have given values much higher than those measured—a result which seems to be due to large-signal effects. Fig. 2 shows experimental results for the CMI 151-152, the slope of the frequency-pushing curves being of the opposite sign to that predicted theoretically. This may arise from cancellations between frequency pushing and other phenomena, and studies are now under way to clear this problem. The consequences of the frequency-pushing spectrum are discussed later.

Methods of Modulation.—The existence of four electrodes and three potentials, one of which controls the beam current and another the frequency, complicates the problem compared to those of magnetrons. The fundamental consideration is to