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A Racetrack Microtron for Millimeter and Submillimeter Wave Generation*

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Summary—**The accelerator described here is an eight-orbit four-sector racetrack microtron possessing strong focusing action. The magnet gap is only 7 mm, and the accelerating cavity is placed in one of the field-free regions. The energy gain per traversal of the cavity can be varied from 0.4 to 1.5 Mev and synchronism obtained by adjustment of the magnetic field strength and the length of the main straight section. A theoretical analysis of the synchrotron oscillations in energy and phase shows that tight bunching can be achieved at almost any point in any desired orbit by changing the frequency of the synchrotron oscillations. This can be accomplished by varying the RF power and therefore the accelerating voltage.**

One particularly attractive operating region gives tight bunching in the third orbit, allowing the construction of a compact machine if desired. For the RF accelerating source used (frequency 2800 Mc) one obtains 20 per cent of the third orbit current in a bunch length of 0.1 mm using dc gun injection (no prebunching). A current of 20 ma was obtained in the third orbit (2.2 Mev) which should be sufficient for the production of milliwatt power in the submillimeter region.

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BUNCHING of an electron beam for frequency multiplication is generally achieved by energy modulating the beam, and passing it through an element with a transit time that depends in some way on the energy. At nonrelativistic energies this element can be a simple drift space (as in a klystron, for example), since at these energies the electron velocity depends strongly on the energy. A second possibility is the use of a deflecting magnetic field, which is more appropriate for relativistic velocities. In a magnetic field the angular velocity of a charged particle is inversely proportional to its total relativistic energy. Therefore the time required to deflect the particle through a certain angle is proportional to its total energy.

Kaufman and Coleman[1] first pointed out that a certain electron accelerator, the microtron or electron cyclotron, can give a highly bunched beam due to this

[1] I. Kaufman and P. D. Coleman, "Electron cyclotron as a source of megavolt bunched electron beams," *J. Appl. Phys.*, vol. 27, pp. 1250–1251; October, 1956.

effect. The microtron, Grinberg,[2] in its conventional form, consists of a re-entrant cavity situated in a homogeneous magnetic field. Electrons injected into the cavity are accelerated across the cavity, then deflected by the magnetic field back to the cavity, again accelerated, and so on. If the strength of the magnetic field and the voltage across the cavity are chosen correctly, then there exists a resonant electron that crosses the cavity in all orbits at the same phase of the RF field in the cavity. The energy of the resonant electron increases at each cavity crossing by the same amount, which has to be a simple fraction of the total energy of the electron at injection.

Bunching of the electron beam is due to two effects connected with the synchotron oscillations of accelerated electrons. By synchrotron oscillations we shall understand oscillations of electrons in the energy-time phase space that take place about the resonant electron. The first effect is the stability of large nonlinear synchrotron oscillations which is limited to the phase stable region. The latter has typically a width of 0.3 radians of the phase of the accelerating RF field. The second effect is an additional phase compression due to small (linear) synchrotron oscillations in the immediate vicinity of the resonant electron. These oscillations can be described by the relations[3]

$$\psi_k = \left[\left(1 - \frac{\alpha}{2\pi}\right)\cos\omega_s(k - \tfrac{1}{2}) + \frac{\alpha}{2\pi}\cos\omega_s(k + \tfrac{1}{2})\right]\cdot\frac{\psi_0}{\cos\frac{\omega_s}{2}} + \left[\left(1 - \frac{\alpha}{2\pi}\right)\sin\omega_s(k - 1) + \frac{\alpha}{2\pi}\sin\omega_s k\right]\cdot\frac{2\pi\chi_0}{\sin\omega_s}$$

$$\chi_k = -\frac{\sin\omega_s k}{\sin\omega_s}\cdot\tan\bar{\phi}_{res}\cdot\psi_0 + \frac{\cos(k - \frac{1}{2})\omega_s}{\cos\frac{\omega_s}{2}}\cdot\chi_0,$$

where

k = the orbit number,

$\psi = (2\pi(t - t_{res}))/T$,

t = the time at which an electron passes an orbit point determined by the orbit angle α (α being measured from the center of the cavity),

t_{res} = the time at which the resonant electron passes that point,

T = the period of the RF field oscillations,

$\chi = (W - W_{res})/\Delta W$,

W = the total energy of an electron,

W_{res} = the total energy of the resonant electron,

ΔW = the energy the resonant electron gains in each orbit,

ψ_0, χ_0 = the defined quantities at injection,

$\omega_s = \cos^{-1}(1 - \pi\tan\bar{\phi}_{res})$ is the angular frequency of the synchrotron oscillations per turn,

$\bar{\phi}_{res}$ = the phase at which the resonant electron passes the center of the cavity.

The possible range of ω_s is

$$0 \leq \omega_s \leq \pi.$$

For $\omega_s = \pi/2$ one obtains the highest acceptance in the accelerator (maximum orbit current).

Since the energy spread at injection is negligible, the terms containing χ_0 in the above equations can be neglected. One finds then that ψ_k becomes zero at regular intervals giving an additional bunching of the electron beam in the vicinity of the resonant electron. The locations of these additional compressions are determined by the value of the synchrotron frequency, which can be varied by changing the voltage across the cavity. They can therefore be made to occur at almost any point of any orbit.

If the nonlinear terms of the synchrotron oscillations are numerically considered, one finds that the highest degree of bunching is generally obtained during the second of the periodically occurring compressions. Since, on the other hand, acceptance is highest for an ω_s of $\pi/2$ one finds that best bunching can be obtained in the third orbit with an ω_s close to the above value. Calculations show that in this case, for a microtron operating at 2800 Mc, approximately 50 per cent of the electrons contained in the beam are to be found within a bunch of 0.3 mm length, and 20 per cent within a 0.1 mm length (Fig. 2). In practice there will be an additional longitudinal spread due to the beam having a finite (lateral) size, but this should not add more than a few tenths of a millimeter to the bunch length.

The microtron in its conventional form has a number of weaknesses that make it difficult to take advantage of its beam-bunching properties. These are lack of a free choice of the energy gain per orbit, lack of magnetic focusing during acceleration, difficult electron injection, and an unnecessarily large magnetic gap due to the fact that it must accommodate the cavity. These difficulties can be avoided if a so-called racetrack arrangement is used, *i.e.*, if the magnetic guide field is split into a number of sectors. A four-sector arrangement has been suggested independently by Roberts[4] and Moroz.[5] Following this suggestion the authors have constructed and operated the racetrack microtron shown in Fig. 4. De-

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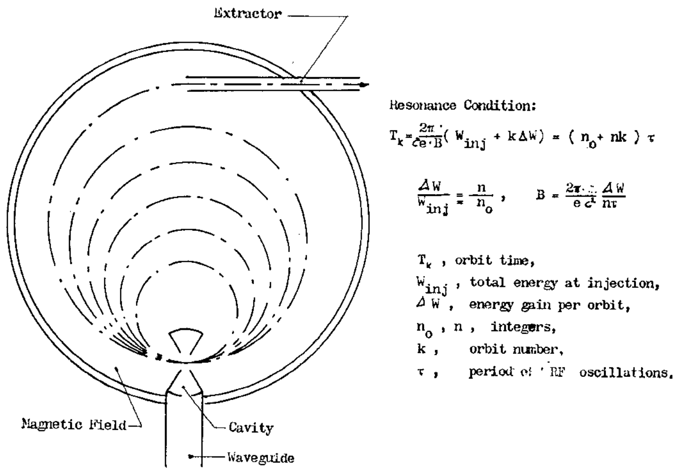

Fig. 1—Schematic diagram of a conventional microtron.

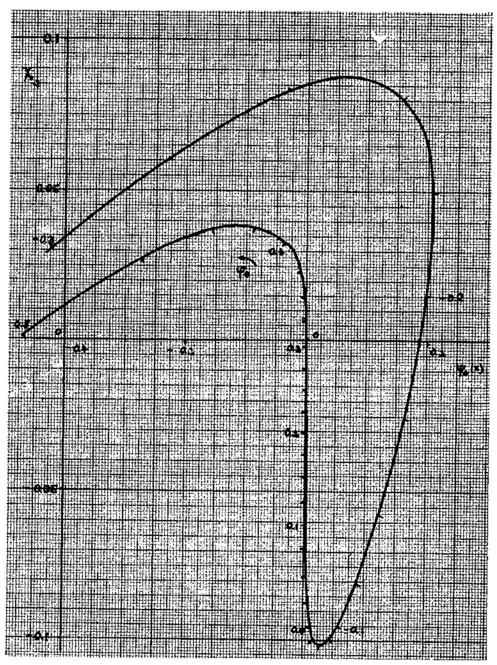

Fig. 2—Electron distribution in the χ, ψ plane in the third orbit. This is a plot of the normalized energy χ_3 of an electron injected at RF phase ϕ_0 against the relative phase ψ_3 of the RF cycle at which the electron passes the midpoint of the third orbit. Both ϕ_0 and ψ_3 are in radians. It is apparent that a large contraction of the electron bunch occurs near the resonant electron.

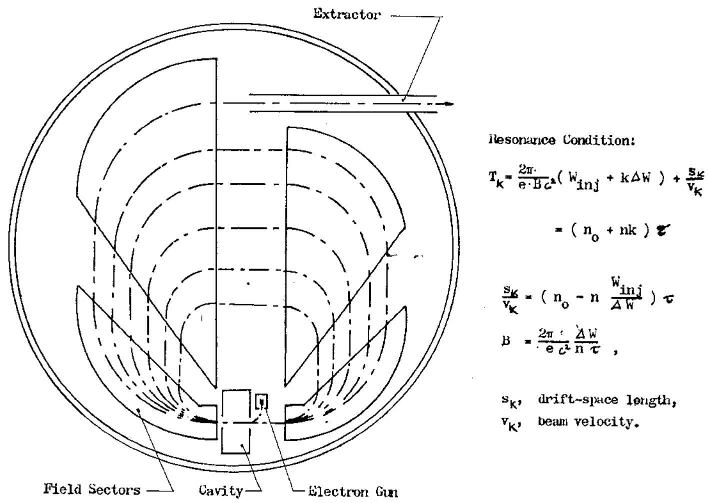

Fig. 3—Schematic diagram of a racetrack microtron.

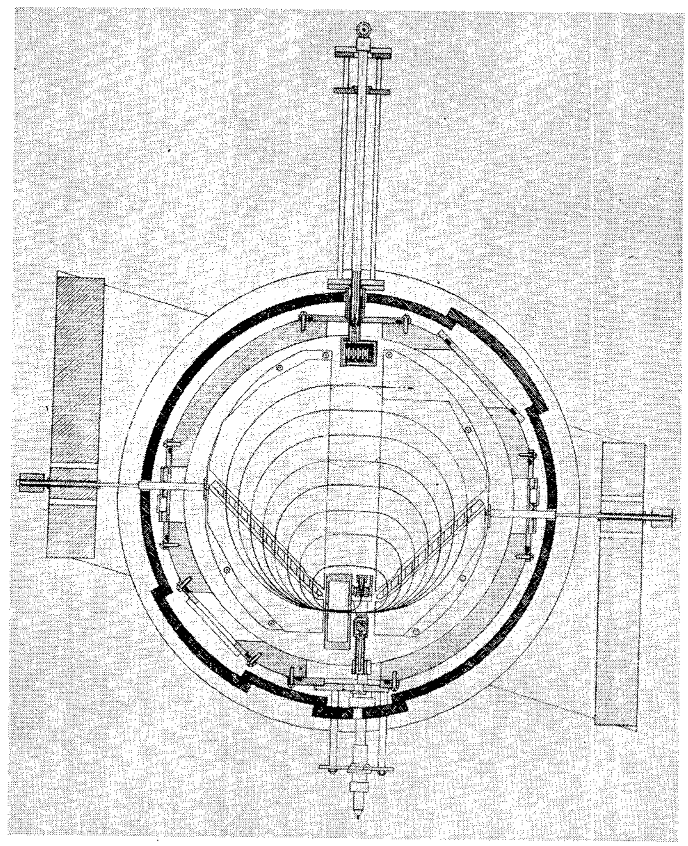

Fig. 4—Detailed diagram of the eight-orbit racetrack microtron.

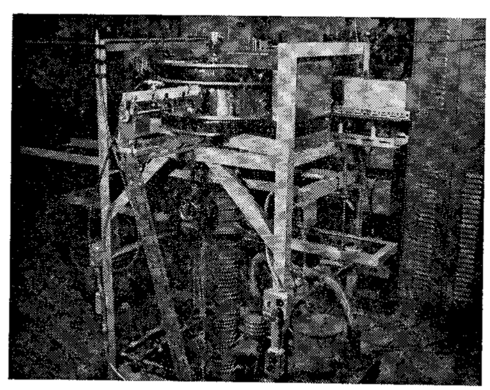

Fig. 5—Photograph of the eight-orbit racetrack microtron.

tails of the resonance conditions are given in Brannen and Froelich[6] and Froelich.[3] The magnetic guide field is split into four sectors with a uniform field within the sectors, and regions of a low magnetic field between the sectors. To obtain stability of the betatron oscillations, thus achieving focusing of the beam, magnetic shields have been installed in two regions between the sectors, reducing the magnetic field in these regions. The magnetic gap within the sectors has a width of only 7 mm. The energy gain per orbit can be varied within wide limits (0.40–1.5 Mev) and synchronism obtained by adjusting the distance between the symmetrical half of the magnetic guide field. The lower limit of the range is determined by the width of the cavity and gun assembly, the upper limit by the power available and RF breakdown in the cavity. With the present arrangement this gives a lower limit of 780 kev per orbit. We have operated as low as 400 kev with the gun removed and field emission from the walls of a re-entrant cavity supplying the current. The upper limit could be as much as 1.5 Mev per orbit if power is supplied by two magnetrons. At the present time one magnetron (RK 5586) is used supplying 600 kw peak power (pulse duration 2 μsec). For electron injection, a simple Pierce gun is used giving a current of 300 ma at 20 kev. The electrons are injected into the cavity by means of small auxiliary pole pieces.

The highest currents obtained to date are 20 ma in the third orbit and 2.5 ma in the final (eighth) orbit with an energy of 6.2 Mev in the eighth orbit. The high current dropoff from third to eighth orbit is due to the fact, that, because of beam loading, the accelerator does not operate in perfect synchronism. With an RF source giving slightly more power than the presently used magnetron, the current in the final orbit should exceed 10 ma. This assumption is substantiated by the fact that at lower currents ($<$1ma) the current drops off from third to eighth orbit only by a factor of 1.5. The bunching behavior of the racetrack microtron is theoretically similar to that of a conventional microtron, *i.e.*, with an optimum bunching to be expected in the third orbit. In an actual submillimeter wave generator a three-orbit machine might therefore be used, giving a fairly compact design, and such a device is being designed on the basis of the present machine. As far as the extraction of electromagnetic radiation from a bunched beam is concerned, we have not been able to use the beam of the racetrack microtron for that purpose in time for this conference. So far we have been using Cerenkov and transition radiators to extract radiation from an electron beam accelerated by a simple cavity. We plan to continue this series of experiments in the near future using the beam of the racetrack microtron.

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The authors are grateful to their colleagues T. W. W. Stewart, V. Rutulis, V. Sells and D. Rumbold for their assistance in the construction and operation of the microtron.

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The Groove Guide, a Low-Loss Waveguide for Millimeter Waves*

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Summary—**A new waveguide for the low-loss transmission of millimeter waves is presented. The guide consists of two parallel conducting walls with grooves in the central region of the guide cross section. The grooves run along the guide in the direction of the wave propagation. It is shown that the waveguide, if excited in the TE-wave mode, has properties similar to those of the H guide, which contains a dielectric slab between the conducting walls in the center. The new guide is characterized by an exponential transverse decrease of the field distributions in direction from the center and by low attenuation. Theoretical considerations dealing with the field distribution and the data of the guide are presented.**

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INTRODUCTION

IT CAN BE SHOWN that a waveguide which consists of two parallel conducting walls has low attenuation if excited by TE waves. For this wave mode, the electric-field vector is parallel to the conducting walls. The attenuation has characteristics similar to those of the circular waveguide excited by TE_{01} waves; namely, it is low and decreases with increasing frequency.

The H-guide, which consists of two parallel conducting walls and a centrally located transverse dielectric slab running along the guide in the direction of the wave propagation, has similar low-loss properties [1, 2]. In