FOUR-SECTOR RACETRACK MICROTRONS*

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Summary. Racetrack geometries of the guide field are capable of freeing the microtron type of electron accelerator from its inherent limitations. Two completed racetrack microtrons of 2.5 and 6.3 MeV energy are described. A possible application of the design features of these accelerators to microtrons of up to 50 MeV is discussed. Preliminary results of a design study for a 200 MeV racetrack microtron are presented.

Electron energies obtainable with a microtron[1,2] in its conventional form, i.e. one consisting basically of a microwave cavity within a homogeneous magnetic field, are limited by the low energy gain per orbit, requiring low magnetic fields and large accelerator sizes, and insufficient beam focusing. For the normal energy gain of 0.511 MeV and the most convenient microwave frequency of 2.8 GHz. the required strength of the magnetic field is only 1000 Oe. Using ingenious injection schemes[3] energy gain and magnetic field strength can be doubled, but are still not high enough to make the microtron an attractive type of electron accelerator.

These conditions do not apply to racetrack microtrons, i.e. microtrons with a magnetic field that is split up into a number of sectors. The resonance condition for racetrack microtrons

$$T_k = \frac{2\pi}{eBc^2}\,(W_{inj} + k\Delta W) + \frac{s_k}{v_k}$$

$$= (n_o + nk)\tau$$

where: T_k = orbit time
W_{inj} = total energy at injection
k = orbit number
ΔW = energy gain per orbit
s_k = drift space length in k^{th} orbit
v_k = velocity in k^{th} orbit
n_o, n = integers
τ = period of rf oscillations

can be satisfied by choosing

$$\frac{s_k}{v_k} = \left(n_o - n\,\frac{W_{inj}}{\Delta W}\right)\tau$$

$$B = \frac{2\pi}{ec^2}\;\frac{\Delta W}{n\tau}$$

The condition can be satisfied for any energy gain by varying either injection energy or drift space length permitting high and continously variable energy gains. Beam focusing in a racetrack microtron can be accomplished in various ways. The accelerators described in this paper, of which the first two are existing devices, the other two design studies, follow in this respect independent proposals by Roberts[4] and Moroz[5]. A four sector geometry is used and the fringe feidls provide beam focusing. Racetrack microtrons have the added advantages of easier electron injection and a reduced width of the magnetic gap, which in turn reduces the power requirements for exciting the magnetic field.

Fig. 1 shows the first microtron of this type built. It is an eight orbit accelerator with a design energy of 12 MeV. The magnetic field in the four sectors is uniform. The gap width is only 7.2 mm, so that the d.c. power required to excite a field of 3000 Oe is of the order of 100 W delivered by a 250 mA constant current supply. The slanted gaps between the sectors contain magnetic shields, which by reducing the stray field to zero equalize the focusing and defocusing effects of the adjacent fringe fields and thus secure stability of the betatron oscillations. The injection system consists of a concentric electron gun with a lanthanum boride cathode and small injecting pole pieces. The gun current is 400 mA, the pulsed gun voltage 25 kV. The beam is accelerated in a cylindrical cavity driven by a single amperex DX 276 S-band magnetron with a power output of 800 KW. The maximum final energy is at the present time 6.3 MeV with a maximum pulsed current of 40 mA. Due to the nature of the experiments performed and shielding problems, so far no attempt has been made to reach the design energy of 12 MeV. This would require a microwave generator with higher power. The energy gain per orbit and therewith the final energy can be varied continously by changing from the outside the distance of the pole pieces from the symmetry axis of the polepiece configuration. Thanks to the large separation of orbits extraction does not present any problems. As in many conventional microtrons the beam is extracted by means of a cylindrical magnetic shield, but in contrast to conventional microtrons there is no appreciable perturbing effect on the lower orbits.

A three orbit 2.5 MeV, 100 mA racetrack microtron is shown in Fig. 2. Its design features are identical to those of the 8 orbit machine, except for its size, yoke configuration and mechanical means of polepiece motion. The

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purpose for which it was built is to utilize certain phase bunching properties of the microtron for submillimeter wave generation[6]. Phase bunching occurs under certain conditions due to the fact that phase points in the central portion of the phase stable region move uniformly around the resonant point. Thus the narrow energy spread of electrons injected into the phase stable region is periodically converted to a narrow phase spread. In the same manner a reconversion to a narrow energy spread occurs periodically, which may make the microtron attractive for applications requiring a narrow energy spread at energies of a few MeV, and for which van de Graaf accelerators are not practical. That this effect is still present even after passage through a moderately high number of orbits was confirmed by using the beam of the eight orbit microtron to generate electromagnetic waves with frequencies of up to 200 times the r.f. frequency of the accelerator. The power generated was in good agreement with the theoretically predicted harmonic content of the beam under the above mentioned phase bunching conditions. Microtrons with a high number of orbits do of course have an inherently narrow relative energy spread, since it cannot be larger than the energy width of the phase stable region which typically is one tenth of the energy gain per orbit.

Accelerators for energies of up to 50 MeV could be built with similiar design features as those of operating racetrack microtrons. Fig. 3 shows a possible configuration for such a device. Stress is here put on simplicity of design, especially of the r.f. system. Here the number of orbits is 16 giving a radius of the final orbit of 28 cm if again S-band microwave power is used for acceleration. The necessary size of the vacuum chamber would be 70 cm, the overall size of the magnet 125 x 70 x 50 cm.

The configuration of the magnetic field is again an array of four sectors with uniform fields and a gap width of 8 mm. Magnetic shields in the two inclined spaces between the sectors provide again a certain control over the frequency of the betatron oscillations. The width of these spaces increases slightly with increasing orbit radius. The angles between its boundaries and the symmetry axis of the configuration are 45° and 42°. This gives a more uniform frequency of the vertical betatron oscillations, which in the 8-orbit microtron described before is approaching zero with increasing orbit number, due to the uniform width of the shields. Here the frequency of the vertical betatron oscillations is of the order of one oscillation per 4 orbits. A more strongly focusing version providing a frequency of one per 1 to 2 orbits seems to be possible in this configuration by increasing the angle between the boundaries of the shielded space, but has not yet been investigated in detail. The energy gain per orbit can again be varied by changing the width of the central space between the pole pieces, which for the energy range considered, and operation in the $n = 1$, $n_o = 2$ mode, would be about 9 cm. The cavity is again a simple cylindrical cavity 4.5 cm long resonant in the TM_{010} mode. The maximum energy gain that can be obtained in this kind of cavity is probably around 2 MeV. This would set the maximum energy of a 16 orbit device at about 30 MeV. A 2 MW magnetron would supply sufficient power to accelerate 30 mA. Higher energies or currents are possible, but would necessitate a more complex r.f. system. A disc loaded cavity operating in the $\frac{2\pi}{3}$ mode or a similar device together with an r.f. generator supplying more than 2 MW could be used to increase the energy to about 50 MeV, with the same basic magnetic field configuration with a wider central region and operation in the $n = 1$, $n_o = 3$ mode. Another possibility of increasing the energy would be to simply increase the number of orbits. Which one is to be preferred would depend on whether weight and space or energy resolution are the prime considerations. The basic simplicity of the design, the efficiency of operation using a constant magnetic field, the ease of beam extraction, small beam divergence, higher current, and a relative energy spread of less than one percent make this kind of accelerator a strong contender for the place presently occupied by betatrons.

Finally, we would like to consider the results regarding racetrack microtrons of energies from 50 to 200 MeV (Fig. 4). Here injection of electrons at energies of a few times the energy gain per orbit seems necessary for the following reasons. The large size of the polepieces and large magnetic fields make it impossible to obtain a variable energy gain by the same method as used in the accelerators described above. This then makes necessary a variable injection energy. The injection magnet on the other hand would occupy the space through which normally the lower orbits traverse. Hence injection at energies of $3\Delta W$ or $4\Delta W$ is necessary. This also eases the problems normally associated with the betatron stability of the lower orbits, problems which here are the more difficult to solve since interaction lengths of the order of 20 cm are here necessary. In fact, guide field configurations simpler than those involving magnetic shields become possible. In the example shown, the guide field consists of sectors of alternating field strength. The ratio B_1/B_2 is equal to 2.25, the beam traverses an angle of 20° in the region with the lower field. This gives inclinations of the boundaries between the various region with respect to the symmetry axis of 50° and 31.5°.

The first stage of acceleration is done by a smaller microtron of 10 orbits and an energy gain per orbit of up to 2 MeV. The beam is then injected into the main accelerator by means of an achromatic translation system with parameters carefully chosen so as not to distort the phase stable region of the first stage beyond the boundaries of the phase stable region of the second stage. The second stage having a larger energy gain of up to 5 MeV has a phase stable region which has a greater energy width but the same phase width. The beam is further accelerated in a disc loaded cavity with the same resonant frequency in the S-band as the cavity of the first stage. The average field in the sectors then must be up to 10,000 Oe, the field in the regions with the larger field up to 10,700 Oe. With a gap width of 1.5 cm in the high field region the power requirement to obtain these fields are rather small. The number of orbits is 30 giving a maximum final energy of 200 MeV and a relative energy spread of 0.25 percent. The chamber diameter required is 1.75 m.

In conclusion it seems apparent that the microtron is only now entering the most important stage of its development.

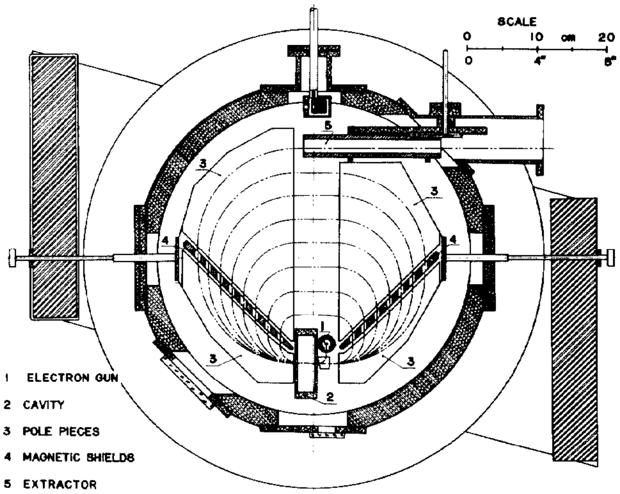

Fig. 1. Diagram of an eight orbit 6.3 MeV racetrack microtron.

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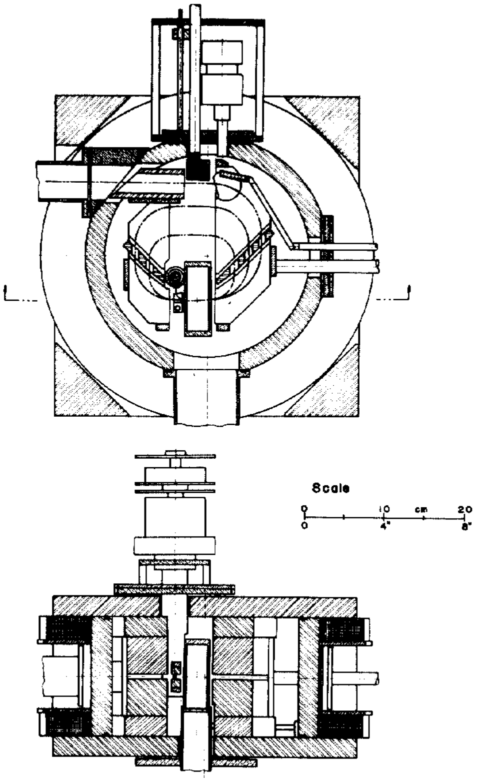

Fig. 2. Diagram of a two orbit 2.5 MeV racetrack microtron.

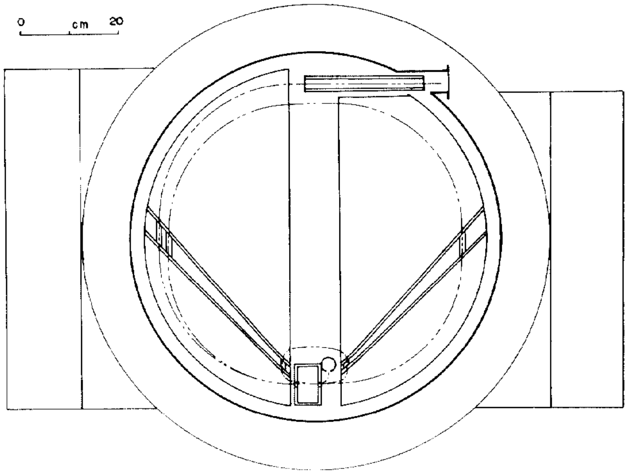

Fig. 3. Schematic diagram of a sixteen orbit 30 MeV racetrack microtron.

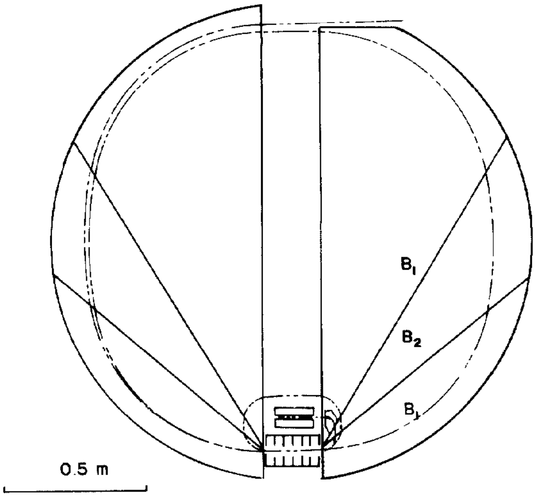

Fig. 4. Schematic diagram of the polepiece configuration of a thirty-six orbit 200 MeV racetrack microtron.