DESIGN OF A 15-MEV CW MICROTRON*

P. P. Wintersteiner and D. S. Edmonds, Jr.

Boston University
Boston, Mass.

Introduction

The microtron, first proposed by Veksler[1] in 1944, is the only cyclical electron accelerator in which the magnetic field remains constant and which is therefore not inherently a pulsed machine. However, in order to reduce the overall size of the accelerator, decrease the number of orbits required to attain a given output energy, and facilitate satisfying the resonance conditions, a large energy gain per turn is highly desirable. Hence most microtrons built and operated to date[2] have in fact been pulsed. In this way high RF fields were obtained with available tubes and at the same time problems of power dissipation and breakdown in the cavity were minimized. On the other hand, the possibility of CW operation is of considerable interest since an accelerator rivalling a Van de Graaff in energy resolution while giving more output energy with smaller size and lower cost can thus be produced. Such machines have been considered by Kapitza et al.[3,7] but have received relatively little attention in this country. Nevertheless, their usefulness in high-resolution, count-rate-limited experiments would seem to justify further investigation. The microtron design presented here permits obtaining a 15 MeV beam with 100% duty cycle.

We approach this design by first estimating how large a peak electric field can be sustained in the cavity under CW RF excitation. A general rule of thumb for this value is 10^7 volts/meter, although Kapitza[3] in his discussion of the CW microtron indicates that fields of 1.5×10^7 volts/meter are quite feasible. For the present work we have chosen 1.25×10^7 volts/meter as a compromise that can be achieved in practice and at the same time allows a reasonable energy gain per turn. This specification places stringent requirements on the vacuum that must be attained, the treatment of the internal cavity surfaces, and the cavity cooling system, but these are not beyond practical realization. Our calculations show that with the electric field amplitude just established, the power dissipated in our cavity will be 68 kW or, with a cavity wall area of 340 cm^2, 200 watts/cm^2. These values are based on a resistivity of 2.3×10^{-8} ohm-meters for copper, which allows for a wall temperature of 100° C. Kapitza[3] has found that for a similar cavity operating at an RF wavelength $\lambda = 20$ cm, an amplitude of 1.3×10^7 volts/meter can be maintained with a dissipated power of 90 kW, necessitating the removal of 150 watts/cm^2. When scaled to our chosen wavelength of approximately 15 cm this becomes 265 watts/cm^2. In any case, since as much as 500 watts/cm^2 can be dissipated by proper cooling arrangements, no difficulty should be experienced on this score. The required driving power is currently obtainable from a number of tubes of which the Varian type VA-858 CW klystron amplifier is a good example. Nevertheless, restricting the electric field amplitude to less than 1.5×10^7 volts/meter is a severe limitation. In order to get a reasonable energy gain per turn it is then necessary to make the cavity considerably thicker than in pulsed machines, and even with the dimension parallel to the beam raised to as much as 4 cm this energy gain is so small that the DC magnetic field must be less than 600 gauss. Thus for a given output energy the final orbit diameter becomes relatively large. The lower energy gain also magnifies the problem of getting an electron up to an energy where its velocity may be considered constant and equal to the velocity of light while still satisfying the resonance conditions. These difficulties can be overcome by adopting the so-called "racetrack" microtron design,[4,5] but direction-focusing problems then arise in the straight sections. If no more than 15 MeV is required, a magnet diameter of about 2 meters is adequate and does not result in an impossibly large structure. We have therefore elected to consider a conventional microtron and investigate whether an injection method can be found that will give satisfactory results with the limited RF field imposed by CW operation.

The High-Energy Orbits

Our design procedure begins with the selection of the phase angle and energy gain per turn for the resonant electron, i.e., the electron which, while traveling with a constant velocity differing negligibly from c, passes through the middle of the cavity with the same phase angle α_r relative to the RF field and receives the same energy increase V_r each time around. The usual phase stability diagrams[6] show that values of α_r near 20° offer a good compromise between having a large phase stable region and getting as much energy gain per turn as possible for a given RF amplitude. Figure 1 shows such plots for $\alpha_r = 19.2°$, which was found to be optimum in the present design. Note that in this work the electric field is taken as a cosine function of time.

*Supported in part by the National Science Foundation.

Following the practice of Kapitza, Bykov, and Melekhin[7] and also of Brannen and Froelich,[8] we have assumed a right circular cylindrical cavity of radius $a = 2.405\ \lambda/2\pi$ and thickness d operating in the TM_{010} mode. V_r is then given in electron volts by

$$V_r = E_o d \frac{\sin \pi \frac{d}{\lambda}}{\pi \frac{d}{\lambda}} \cos \alpha_r \qquad (1)$$

where E_o is the amplitude of the electric field at the cavity center. Figure 2 shows a family of plots of equation (1) from which V_r may be read as a function of λ for various d and for the values $E_o = 1.25 \times 10^7$ volts/meter and $\alpha_r = 19.2°$ already established. Choosing V_r determines the DC magnetic field B_o for a particular RF wavelength through the relation

$$B_o = \frac{2\pi\ V_r}{c\ \lambda} \qquad (2)$$

which expresses the condition that the resonant electron slip in phase by one RF period in successive orbits. If the cavity thickness is not allowed to become so great as to interfere with the first orbit, values of more than about 400 KeV cannot be expected for V_r. With λ = 15 cm the corresponding magnetic field is about 560 gauss, whence the final orbit radius becomes a little over 90 cm. The size of the machine is thus pretty well fixed, as is the necessity for avoiding any disturbance in B_o which might be an unduly large percentage of the relatively small value just established. We have accordingly set up as a constraint on our design the requirement that the DC magnetic field shall not be less than 500 gauss, but beyond this, d, λ, α_r, and hence V_r and the actual value of B_o must be chosen so that electrons come out of the early orbits in the proper phase and also satisfy the other resonance condition

$$V_o + V_{inj} + \Delta V_1 + \Delta V_2 = 4V_r \qquad (3)$$

Here V_o is the electron rest energy, V_{inj} is the kinetic energy after the passage through the cavity immediately following injection from the cathode, and ΔV_1 and ΔV_2 are the energy gains obtained in the cavity traversals coming at the ends of the first two full orbits (see Figure 3). Equation (3) expresses the requirement that the third orbit take an integral number of RF periods to complete. Note that ΔV_2 is often negligibly different from V_r, in which case (3) reduces to $V_o + V_{inj} + \Delta V_1 = 3V_r$. In any event we assume that for all subsequent passages the electron velocity is sufficiently close to c so that the energy gain corresponding to the resonant phase is V_r. For the present work we choose V_r to be 390 KeV.

Injection and Low Energy Orbits

Introduction

Of the various methods that have been proposed for injecting electrons into a microtron from a thermionic cathode, we have here chosen the one suggested by Kapitza et al.[7] in which the cathode is placed on the exterior cavity wall at an appropriate distance from the axial center line and directs an electron beam into the cavity as shown in Figure 3. A combination of the electron gun location, the direction and energy of the injected beam, and the RF frequency must be found that will allow electrons entering in at least some range of phase angles to be captured into stable orbits. To do this the relativistic equations of motion must be solved both in the DC magnetic field B_o and in the combination of B_o and the RF electric and magnetic fields associated with the TM_{010} mode in the cavity. Referred to the coordinate system illustrated in Figure 3 (with the z-axis perpendicularly up out of the paper) the fields in the cavity at the orbit plane are

$$\vec{E} = \vec{i}\ E_o\ J_o\ (2.405\ \tfrac{y}{a})\ \cos\ (\omega t + \varphi) \qquad (4)$$

and

$$\vec{B} = \vec{k}[-B_o - \tfrac{1}{c}\ E_o\ J_1(2.405\ \tfrac{y}{a})\ \sin(\omega t + \varphi)] \qquad (5)$$

where J_o and J_1 are the zeroth and first order Bessel function of the argument 2.405 y/a. The equations of motion were reduced to four first-order differential equations and solved on Boston University's IBM model 1620 digital computer for a wide range of initial conditions. The procedure was as follows: First λ was selected determining B_o in view of our having chosen V_r = 390 KeV. Then α_r and d were adjusted so that V_r would in fact have this value while at the same time the first orbit would miss the cavity. Next the initial conditions (entering beam energy, angle, and phase) were adjusted in an attempt to get the proper energy and phase for electrons in the first orbit. The main problem here was not one of obtaining sufficient energy for these electrons but lay, rather, in the fact that they would leave the cavity "too late", i.e., at a phase angle relative to the RF field too large to permit their reentering the cavity in the phase necessary for proper acceleration on this passage. Note that since the orbit time in the constant magnetic field is proportional to the electron's total energy, the larger the energy obtained on the injection semiorbit, the later the electron arrives for its first axial traversal of the cavity.

Injection Semiorbit and First Orbit

We observed that for certain injection phases φ we could get electrons of nearly 400 KeV from the injection semiorbit (the passage through the cavity immediately following injection) and that the first-orbit energy so obtained depends more critically on φ than on anything else. However, we found that no matter what the combination of injection phase and energy, the phase at the exit from the cavity is almost always greater than 60^o (with respect to the maximum of the electric field in the accelerating direction taken as 0^o). In fact, an energy greater than 300 KeV causes the first orbit to take so long that the first cavity traversal (i.e., the passage through the cavity following the first orbit) occurs when the RF phase is far past 0^o. On the other hand, energies less than 260 KeV do not usually permit the electron to avoid striking the cavity on its first turn. Thus the range of energies acceptable for the first orbit is very restricted. It appears that the problem cannot be eliminated by altering λ, d, and hence B_0 without going to an α_r which has a very small phase-stable region. Figure 4 shows how the energy in the second orbit depends on that in the first when the injection semiorbit's exit phase angle is 67^o. The smaller energies on the first orbit cause too early an arrival at the start of the second cavity traversal while the larger ones cause too late an arrival. Optimum first-orbit energy (as far as energy in the second orbit is concerned) is seen to be 278 KeV.

The first orbit energy, which is the V_{inj} of equation (3), depends on the energy of the entering electrons as well as on φ. The electrons entering with lower energies provide an exit phase considerably smaller than those with the higher entering energies, meaning they spend less time in the cavity, and their first-orbit energies are not too low for consideration. Table I shows typical energies at the exit from the semiorbit corresponding to various φ for input kinetic energies of 50 and 10 KeV. These figures are for injection straight into the cavity parallel to its axis. The output energies V_{inj} can be altered by a few percent by varying the position of the injection point along the cavity wall, and sometimes this proves convenient. There is no reason why the electron has to come out exactly on the axis of the cavity. Of course, in constructing an actual microtron, holes have to be drilled in the cavity faces at the appropriate points, but these do not usually disturb the RF field appreciably. It turns out that the direction in which the electron is moving at the exit from the injection semiorbit is always quite close to being parallel to the cavity axis. One effect of this is to place the center of the circular first orbit not half-way through the cavity on line OO' (Figure 3) as would be desired but rather to the left thereof. When φ is between 165^o and 180^o, the center of this circle is shifted furthest towards OO'. It is shifted away to the left for smaller φ. Low entering electron energies tend to move the center toward OO'.

One can also vary the direction of the entering electron beam. The effect of tilting the electron gun slightly ($\sim 10^o$) towards the axis is noticeable in that it usually produces a small decrease in the phase at exit and in addition may increase the exit energy by several percent. It also changes the direction of motion at exit so that the first orbit's center is again shifted away from OO'.

First Cavity Traversal and Subsequent Orbits

The problem of matching injection conditions to the resonant electron's perfect orbit was attacked by requiring that on the third cavity traversal the electron gain 390 KeV, that it have a phase α_r, and that its total energy prior to this traversal be 1560 KeV so as to satisfy condition (3). This puts no restriction on the energy gain of the first traversal, which must be adjusted so that the 1049 KeV of kinetic energy required in the third orbit is attained. Even with this latitude no set of injection conditions was found permitting all these requirements to be met. In the best cases the required energy is realized on the third orbit but the phase is such that the electron always arrives for the third cavity traversal too soon and subsequently drops out of resonance.

Fortunately, the arrival error is on the early side so that a possible solution to the problem is to introduce something that lengthens the third orbit without altering the associated energy. For example, this orbit might be made to pass through a short piece of iron pipe which shields it from the DC magnetic field and thus introduces a "straight section" into the otherwise circular path. If this section is inserted at the back of the orbit parallel to the cavity axis as shown in Figure 3, the right-hand half is shifted to the right, giving the additional effect of moving the orbit center back towards OO'. The straight section length provides an independent phase adjustment which can be used to bring the electron into the cavity for the third traversal at both the correct energy and the correct time. Means for following the electron through the straight section and hence determining the length required (by noting when the optimum phase angle was obtained) were written into the computer program. For the case illustrated in Figure 3 this length was found to be 0.378 cm. We believe this to be a practical solution, as straightening the electron path by such means has been used in microtrons before, not only to provide extraction from the final orbit but also to shape early ones.[9] Since we are applying the correction in the third orbit where the electrons are fairly energetic, no pronounced effects due to field inhomogeneities at the pipe ends are expected, and as the second and third orbits are separated by 5.36 cm at the point directly in back of the cavity, there should be no perturbation of orbits other than the third. We also note that since only one orbit is treated in this way, the disturbance is not periodic, hence no beam oscillations should result.

Summary of Results

With the above-described adjustments a CW microtron should be realizable producing an output energy of 15 MeV in 39 turns. The salient design characteristics of this machine are listed in Table II and the early orbits are plotted in Figure 3. An investigation of the dependence of orbit stability on the angle of injection shows that this is critical. For the chosen conditions electrons injected more than 1° from the assigned input beam direction (10° to the cavity axis) will not be accepted into stable orbits. Thus an electron gun is necessary which will provide a large current within a very small angular spread. In addition, deviations from the chosen entering phase angle of more than half a degree will result in the subsequent orbits being unstable. The accelerator thus starts off by reducing the intensity of the beam injected into the cavity from the cathode by a factor of 360. Nevertheless, with an efficient electron gun and good homogeneity in the magnetic field, final beam currents approaching 100 μa should be obtainable.

References

1. V.I. Veksler, DAN SSSR 43, 346 (1944). See also J. Phys. U.S.S.R. 9, 153 (1945).
2. For a list, see A. P. Grinberg, Usp. Fiz. Nauk 75, 421 (1961).
3. S. P. Kapitza, Elektronika Bol'shikh Moshtnostei (High Power Electronics) No. 4, 178 (1965. Translation available from the authors.
4. E. Brannen and H. Froelich, J. Appl. Phys. 32, 1179 (1961).
5. Proposals for high energy CW microtrons have been advanced by P. Wilson at Stanford and by P. Axel and A. Hanson at Illinois.
6. C. Henderson, F. F. Heymann and R. E. Jennings, Proc. Phys. Soc. (London) 66B, 41 (1933).
7. S. P. Kapitza, V. P. Bykov, and V. N. Melekhin, JETP 41, 368 (1961).
8. E. Brannen and H. Froelich, private communication.
9. D. Aitkin, F. Heymann, R. Jennings, and N. Kalmus, Proc. Phys. Soc. (London) 77A, 769 (1961).

Table I

Typical Energies in the First Orbit for Various Entering Phases and Initial Kinetic Energies of 50 and 10 KeV.

	50 KeV		10 KeV	
φ	Exit Energy (KeV)	Exit Phase (deg)	Exit Energy (KeV)	Exit Phase (deg)
120	365	65	280	60
133	370	80	305	65
150	325	90	295	70
160	295	100	290	70
165	280	100	270	75
170	270	100	260	75
175	265	100	250	75
180	260	100	245	75

Table II

Characteristics of a 15-MeV CW Microtron

Output energy:	15.2 MeV
Number of turns:	39
Cavity	
Type :	Right circular cylinder
RF mode:	TM_{010}
Radius:	a = 5.80 cm
Thickness:	d = 3.75 cm
Operating frequency:	f = 1980 Mc/s
Wavelength:	λ = 15.15 cm
Electric field amplitude at center:	$E_o = 1.25 \times 10^7$ volts/meter
Injection	
Initial kinetic energy:	10 KeV
Initial phase:	$\varphi = 166^o$
Injection angle:	10^o to cavity axis
High-energy orbits	
Energy gain per turn:	V_r = 390 KeV
Resonance electron phase:	$\alpha_r = 19.2^o$
Straight section	
Location:	Back of third orbit
Length:	0.378 cm
Magnet	
DC field :	B_o = 540 gauss
Radius of final orbit:	97 cm

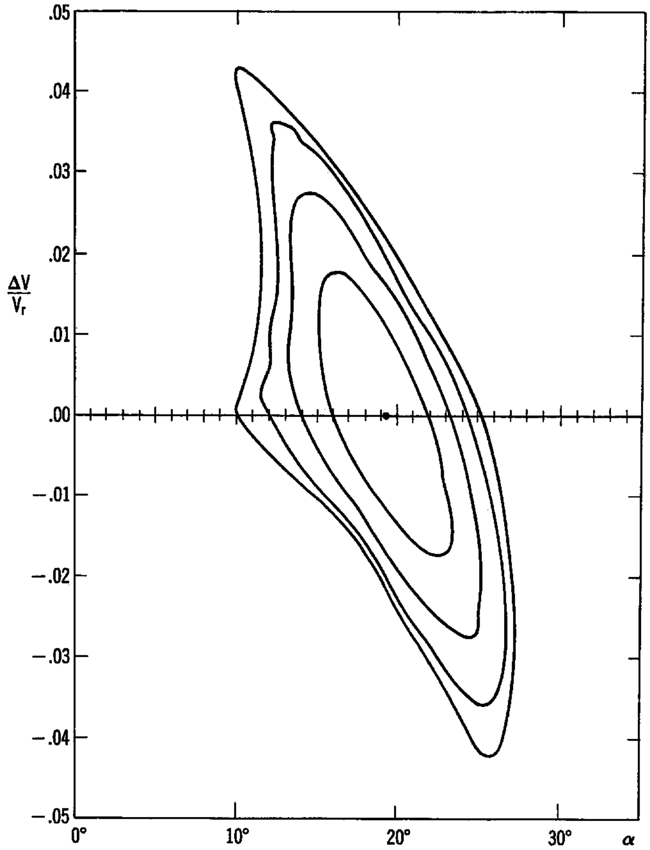

Fig. 1. Phase Stability Plots. $\alpha_r = 19.2°$.

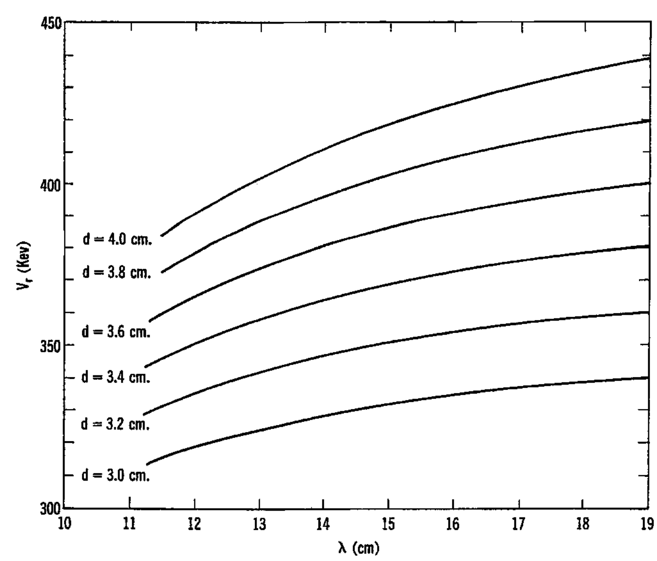

Fig. 2. Plots of V_r as a Function of λ for Various d. $E_o = 1.25 \times 10^7$ volts/meter. $\alpha_r = 19.2°$.

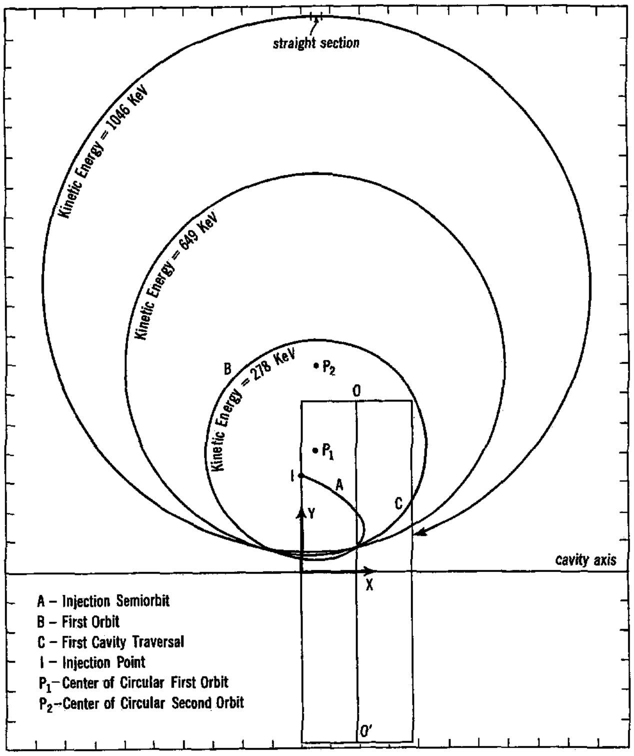

Fig. 3. The Cavity and Early Orbits in the 15-MeV Microtron.

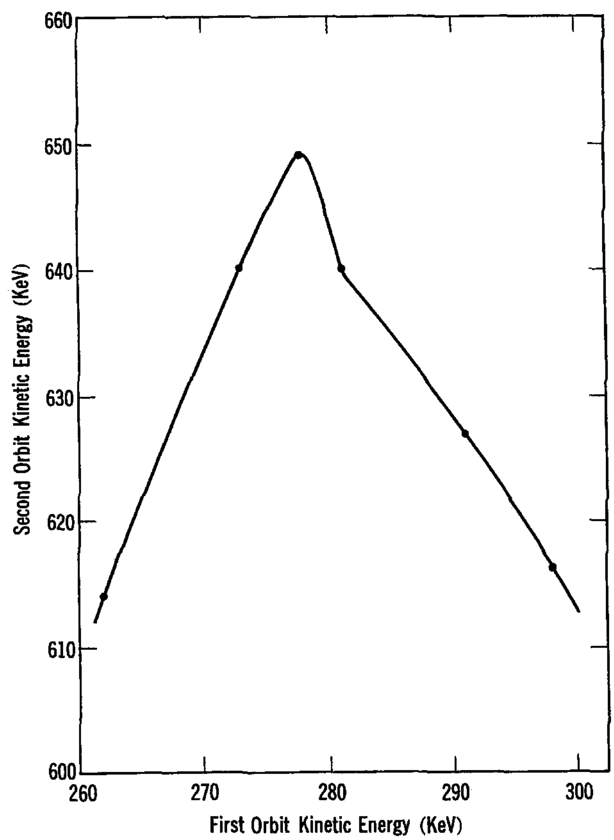

Fig. 4. Dependence of Kinetic Energy after First Cavity Traversal on Kinetic Energy after Injection Semiorbit. Phase at Semiorbit Exit ≈ 67°.