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Improved resonance in microtrons by orbit shaping

V B ASGEKAR, R K BHALLA, M R BHIDAY,
V N BHORASKAR and B S RAYE
Department of Physics, University of Poona, Poona 411007

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Abstract. Microtron electron accelerators generally show a 50% reduction of the injected beam in the first orbits. A modification of the race-track magnet system is proposed in this paper to reduce the beam losses. Calculations of the phases of electrons at the microwave cavity yield exact shapes of different orbits required for resonance in a split magnet system. Introduction of small sector magnets in the field-free space provides a feasible method for obtaining the calculated orbit shapes.

Keywords. Microtron accelerators; orbit shaping.

1. Introduction

A microtron electron accelerator, whether conventional (Redhead 1950) or race-track (Roberts 1958) shows nearly a 50% beam loss in the first few orbits. It is shown by Bhiday *et al* (1972) that velocity corrections for resonance could be applied in order to avoid the beam current losses by adjusting the field-free space in a race-track microtron. Such a design leads to machining difficulties. For low energy microtrons ($\approx$ 10 MeV), use of the race-track magnet is not essential, and the more practicable conventional magnet design is recommended by Kapitza (1962). However, it is advantageous to keep the microwave cavity in a field-free space for efficient external injection of the beam. The race-track design, therefore, needs improved calculations of the first few electron orbits with consequent new design of the magnetic field configuration.

This paper describes such a design for a 10 MeV microtron which makes it possible (i) to keep the cavity in the field-free space, and (ii) to accelerate the electrons in the first few orbits without any phase errors due to velocity corrections. Once the electrons have nearly approached the velocity of light, they pass through a magnetic field distribution similar to that of the usual race-track machine.

2. Theory

Injection of external electrons in a conventional microtron can be achieved in two ways, (*a*) by introducing the thermionic cathode through one side of the cylindrical cavity (Kapitza 1962) and (*b*) by cutting the poles of the magnet suitably to produce a field-free gap for introducing the cavity and thermionic source. In the case of (*a*), the difficulties are mainly concerned with heating and overloading the cavity, requiring a very high power microwave supply and efficient water cooling of the cavity.

In the other alternative (*b*), the resonance condition is upset because the orbit is now no longer a complete circle, and the field-free gap length of the magnet is traversed by electrons of increasing velocity. It is possible to maintain resonance by providing a different magnetic field for each orbit. This distribution of the magnetic field in the conventional microtron, besides being difficult to achieve, leads to unstable betatron oscillations in the vicinity of the cavity. These difficulties can be overcome in the following way.

The conventional microtron is split into two halves (X and Y), and the cavity is now placed in the field-free space as shown in figure 1. The time taken by an electron to complete its path in the two halves for any orbit should be an integral multiple of radio frequency period τ. To achieve this, following Wernholm (1964), the energy gain per turn eV_R should be

$$eV_R = \frac{m_0c^2 + E_{\text{injection}}}{(\mu/\nu - 1)} \tag{1}$$

where, the integers μ and ν define the mode of operation. The uniform magnetic field in the two halves is given by

$$B = \frac{T}{eR}\,[1 - (1-\beta^2)^{1/2} + \tfrac{1}{4}(1-\beta^2) + \cdots] \tag{2}$$

where $\beta = v/c$, and T is the kinetic energy of an electron in an orbit of radius R.

The resonance condition will be satisfied if the time taken by an electron to traverse the total field-free space in any orbit is an integral number of radio frequency periods. The Illinois machine (Robinson 1967) for 600 MeV uses a split magnetic

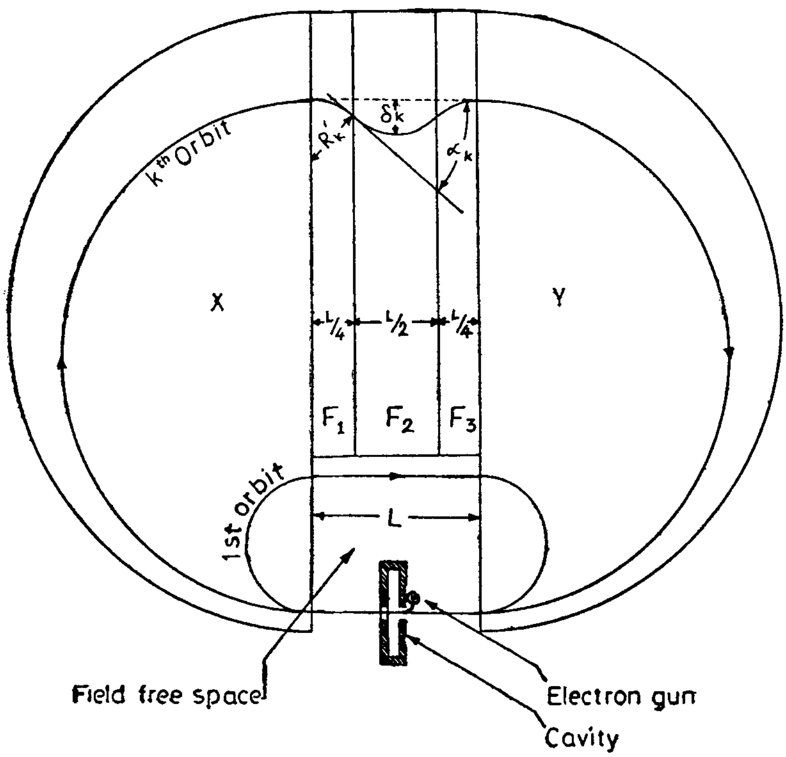

Figure 1. Orbit shaping for the first few orbits.

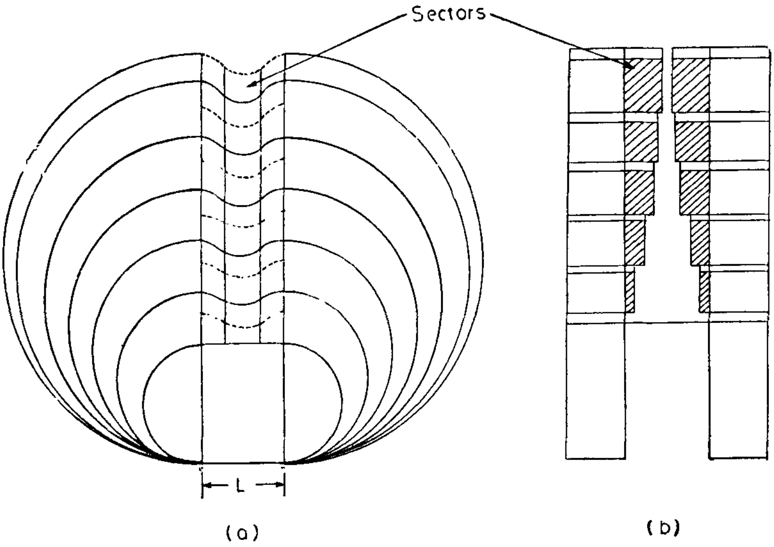

Figure 2. Magnet pole pieces for the first few orbits (*a*) Plan, (*b*) Side view.

field design with a multiple cavity. However, we are concerned mainly with a low energy machine ($\approx$ 10 MeV), using a single cavity. The resonance condition can be achieved with the split magnet and a single cavity, if the field-free space is suitably modified. In the split microtron (figure 1) the time taken by an electron to traverse the field-free space will decrease as the orbit number increases. This decrease in time could be compensated by providing suitably calculated additional paths in every orbit. In the first orbit, however, the length of the field-free space is so chosen as to achieve resonance with a straight path. Successive orbits in a microtron are sufficiently well separated. This enables electron paths between X and Y to be suitably lengthened by providing curvatures in them. In our design these curvatures are produced by small sector magnets placed in the region between X and Y.

Let L be the separation between X and Y which is also half the distance traversed by the electron in the field-free space in the first orbit. The successive orbits have to increase in length gradually. Let, therefore, L_k be the total distance that would be traversed by an electron in the kth orbit between X and Y. Then

$$L_k = L + L_k' = \eta v_k \tau \tag{3}$$

where L_k' is the actual length of the curved path of electrons as shown in figures 1 and 2 and η is an integar. It is possible to achieve the curved passage of electron over L_k' by making it pass through regions F_1, F_2 and F_3 (*see* figures 1, 2) of the gap between X and Y. Fields in regions F_1 and F_3 are directed downwards into the paper, and field in region F_2 is directed upwards from the paper, while their magnitude B_k' is the same in both the cases. The length of the region F_2 is chosen to be $L/2$ so that the upward deflection produced in this region compensates the total downward deflection produced in F_1 and F_3. The deflection in F_1 can be calculated from the expression.

$$\frac{\sin \alpha_k}{\alpha_k} = \frac{L}{L_k'} \tag{4}$$

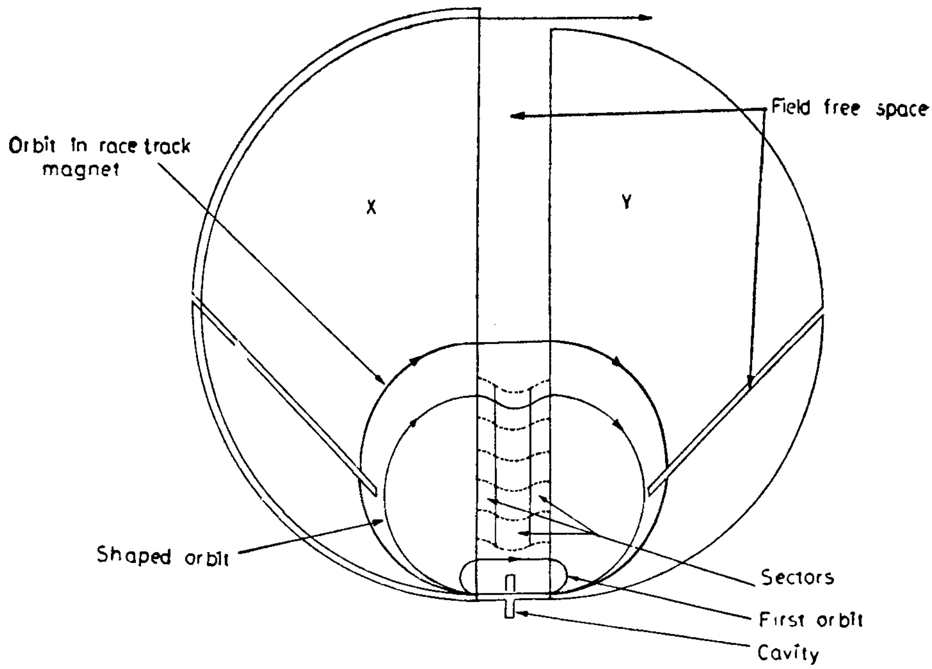

Figure 3. Complete geometry of the magnet pole pieces for the microtron, showing additional two field-free spaces.

The radius of curvature R_k' is related to the angle of deflection α_k by

$$L = 4R_k' \sin \alpha_k \qquad (5)$$

which in turn decides the magnetic field B_k' according to eq. (2).

Each succeeding orbit is shaped similarly until the electron velocity approaches that of light. Beyond this stage L_k' will be constant and can be provided by introducing two-additional field-free gaps, or alternatively by making the microtron a four sector machine as shown in figure 3.

3. Design of proposed 10 MeV microtron

In the proposed design, it is convenient to make the electron's time of traversal within the two halves, X and Y, in the first orbit equal to 2τ. This time increases by τ for each succeeding orbit. The magnetic field and gain per turn are calculated from eqs (1) and (2) for 100 keV injection energy.

The dip, δ_k in the electron trajectory between X and Y is given by

$$\delta_k = \tfrac{1}{2} L \tan \alpha_{k/2}$$

It is clear that δ_k should be less than the orbit separation, which is ~ 3 cm for the microwave frequency of 3000 MHz used in most microtrons. This is possible when the time required to travel L_k is only one period τ. The lengths L_k' for all succeeding orbits are calculated from the electron energy in the kth orbit. Table 1 shows the calculated values of R_k', L_k' and B_k' for the first six orbits of the 10 KeV microtron.

The field directions in the regions F_1 and F_3, reversed to that in region F_2, are achieved by providing separate magnetic circuits. The variation of the magnetic

Table 1. Design parameters for the first 6 orbits of the 10 MeV microtron
Injection energy = 100 keV; Gain per turn = 609 keV
Magnetic field in the two halves of the magnet = 1276·7 Gauss
For first orbit $L = L_1' = 4\cdot539$ cm

Orbit No.	Velocity cm/sec × 10^{10}	Energy keV	R cm	L_k' cm	R_k' cm	B_k' Gauss
1	2·723568	1218·352	2·889	4·539	∞	0
2	2·879221	1827·528	4·496	5·058	1·586	3487·4
3	2·931748	2436·704	6·102	5·233	1·436	5364·1
4	2·955746	3045·880	7·708	5·313	1·388	7073·0
5	2·968700	3655·056	9·313	5·356	1·366	8717·1
6	2·976483	4264·232	10·919	5·382	1·353	10327·9

field from orbit to orbit in the regions F_1, F_2 and F_3 are obtained by using sectorial pole shoes with different pole gaps as shown in figure 2b. The three sectors in F_1, F_2 and F_3 are designed for double focussing.

Calculations indicate that from the seventh orbit onwards, the electron can be accelerated in the usual race-track design. The additional path $(L_k - 2L)$ is now the same for every subsequent orbit and its value is calculated to satisfy the resonance condition. The design parameters for such a four sector race-track acceleration are given in table 2. The entire magnetic field configuration is shown in figure 3.

Table 2. Design parameters for the race-track part of the 10 MeV microtron

Orbit No.	Energy keV	Radius cm	L_k' cm	$L_k' - 2L$ cm
7	4873·232	12·525		
8	5482·584	14·131		
9	6091·760	15·737		
10	6700·936	17·343		
11	7310·112	18·949	5·620	1·080
12	7919·288	20·555		
13	8528·464	22·161		
14	9137·640	23·767		
15	9746·816	25·373		
16	10355·992	26·978		

4. Conclusion

Nearly 50% of the injected beam is lost in all the microtrons so far constructed. Once the electrons become ultra-relativistic, there is no further loss in the beam intensity. The exact analysis of the orbit shape is made using detailed calculations of the phase errors due to velocity discrepancies in the first few orbits. From this analysis introduction of small sector magnets in the field-free space provides a method to shape the orbits as required by the calculations. Exact resonance is now possible in all the orbits.

Such a magnet system is under construction in this laboratory. This will be used with the microwave power system of the 8 MeV Berkeley microtron in this department.

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References

Bhiday M R, Bhoraskar V N, Bhalla R K and Asgekar V B 1972 *Proc. Nucl. Phys. Solid State Phys. Symp.* **15B** 495
Kapitza S P, Bykov V P and Melekhin V N 1962 *Sov. Phys.-JETP* **14** (2) 266
Redhead P A, LeCaine H and Hendeson W J 1950 *Can. J. Res.* **A 28** 73
Roberts A 1958 *Ann. Phys. (New York)* **4** 115
Robinson C S 1967 *Technical Report No.* 156 University of Illinois
Wernholm O 1964 *Ark. Fys.* **26** 527