DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

THE MICROTRON

By

A. P. Grinberg

FTD-TT-62-211-1+2+4

UNEDITED ROUGH DRAFT TRANSLATION

THE MICROTRON

By A. P. Grinberg

English Pages: 66

Source: Uspekhi Fizicheskikh Nauk, No. 3, Vol. LXXV (1961), pp 421-458

SC-1044
ASTAR 2670
SOV/53-61-75-3

PREPARED BY:

TRANSLATION SERVICES BRANCH
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

FTD-TT-62-211-1+2+4 Date Mar. 16 19 62

P

FIRST LINE OF TEXT

FIRST LINE OF TITLE

THE MICROTRON

A.P. Grinberg

Introduction

The microtron is a cycle resonance electron-accelerator having a constant (in time) master magnetic field. Electrons are accelerated by a high-frequency electrical field created in a hollow resonant cavity; a special type of resonance acceleration is used: "resonance with a variable multiplicity factor."

The idea of the microtron was put forth by V. I. Veksler in 1944* [1]. After this, only a few works appeared in the course of several years in which the various aspects of the operation of this accelerator are discussed [2,3]. The first description of a working microtron, built by a group of Canadian physicists, was published in 1948 [4,5]. Certain properties of the microtron and, in particular, the possibility of obtaining very short electron clusters at a good energy uniformity of particles attracted the attention of the many laboratories to this accelerator. As a result, at the present time in the various countries of the world, one may count up to fifteen working microtrons. Chiefly, these are apparatus designed to accelerate electrons to 2.5 or 5 Mev;

*In a number of articles it has been stated that the idea of the microtron was independently put forth by Schwinger, and also Alvarez; however, these ideas were not published.

only in one microtron are electrons accelerated to 29 Mev.

Until recently the main drawback in most working microtrons has been low electron current yield; the average (with respect to time) electron current with an energy of about 5 Mev did not exceed 1 μ a. The second essential drawback of the microtron was that its pole diameter was several times greater than that of the betatron or synchrotron pole, at the same final electron-energy.

Some interesting articles have appeared recently in which experimental studies of the working of the microtron are described [6, 7]. The new ideas in the article by S. P. Kapitsa, et al. are of special interest [7]. Their results show that the microtron, after the introduction of a few comparatively simple improvements, can provide electron beams of very high intensity and can be considerably more compact than earlier microtrons.

In the present survey, an examination is made of the basic experimental and theoretical data on the microtron, the technical parameters of all known microtrons are given, the place of the microtron among a number of other electron accelerators is described, and various applications of the microtron are examined.

1. Conditions of resonance electron-acceleration

Various operating conditions of the microtron.

All microtrons built up to this time are of a single type: a magnetic field is created in a gap between the cylindrical poles of an electromagnet, and an accelerating resonant cavity is placed close to the edge of the pole. The ideal electron path is in the form of a flat spiral all turns of which are by circles osculating at a single point (Fig. 1). These coils of the path are customarily called orbits. After the first transit through the resonant cavity, the electron moves along the "first orbit," after the second transit, it moves along the second orbit, etc.

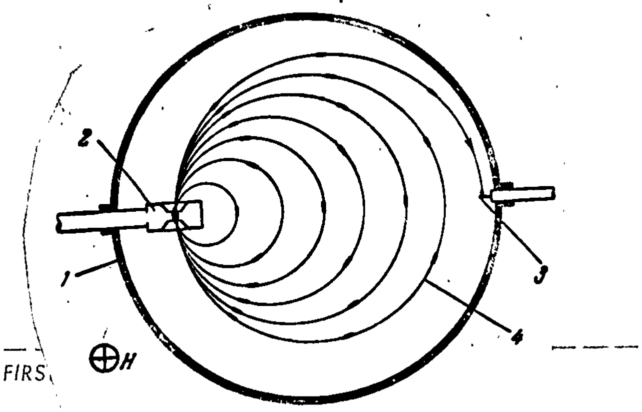

Fig. 1. Diagram of the microtron.
1--vacuum chamber; 2--resonant cavity; 3--target; 4--electron path. The position of electron clusters located simultaneously in the chamber is shown. The lines of force of the master magnetic field are perpendicular to the plane of the drawing.

The accelerating voltage acting in the resonant cavity is described by the formula

$$V(t) = V_\alpha \cos \omega_y t = V_\alpha \cos 2\pi \frac{t}{T_y}. \tag{1}$$

Let us find the conditions of the resonance acceleration of an electron in a microtron. This problem will be examined here more systematically (without unjustified assumptions) than in other articles on the mocrotron.

Let us, as usual, consider resonance acceleration as that process in which an electron has the same phase* at any intersection of

---

*The phase φ of an electron is that value of the phase of the HF-field which occurs at the moment the electron passes through the middle of the accelerating slit. The numerical value of the phase is always given in limits $(-\pi, +\pi)$ using the relation $\varphi = \omega_y t - n\pi$, n is an integer.

the accelerating slit. Let us, however, make the reservation that for the first intersection of the slit, this requirement is not to be considered compulsory. Thus, it is required that

$$\varphi^{(2)} = \varphi^{(3)} = \ldots = \varphi_s = \text{const.} \tag{2}$$

The phase φ_s is called the equilibrium or resonance phase, and an electron satisfying Condition (2) is called a <u>resonance electron</u>.

The energy gain of an electron when passing through the resonant cavity is expressed by the familiar formula

$$\Delta W = eV_a \frac{\sin \theta/2}{\theta/2} \cos \varphi, \tag{3}$$

where θ is the so-called transit phase angle:

$$\theta = \omega_y \tau, \tag{4}$$

τ is the transit time of the accelerating slit, φ the phase of the electron. Note that Formula (3) is valid with high accuracy under the following conditions: 1) the electron moves in a uniform HF field parallel to the lines of the field; beyond the limits of the accelerating slit the strength of the electrical field is zero; 2) the relative change in the velocity of an electron connected with its transit through the accelerating slit is very small, i.e., $(v_2 - v_1)/v_1 \ll 1$. The second condition in particular is always fulfilled for electrons when $v_1 \approx c$.

In working microtrons the magnitude of ΔW is not lower than $\sim$ 250 kev, and in most cases $W \simeq$ 500 kev. Under these conditions, the time τ varies by not more than 26% in all passes of the electron through the resonant cavity, starting from the second pass, because already at an energy of 250 kev the velocity of the electron equals 0.74 c. The function $(\sin \theta/2)\theta/2$ in the range $0 < \theta < 40°$ changes very slowly, so that at these small changes in the magnitude of τ (and θ correspondingly) the value of the factor $(\sin \theta/2)/\theta/2$ in Formula (3) is for all practical purposes unchanged. Therefore it may be assumed that the magnitude of τ is not a function of the "acceleration number" (ν), if $\nu > 1$, and is determined by the formula

$$\tau = \frac{d}{c} = \text{const}, \tag{5}$$

where **d** is the length of the accelerating slit. Therefore, at $\nu > 1$

$$\frac{\theta}{2} = \frac{1}{2}\omega_y \frac{d}{c} = \frac{\pi d}{\lambda} = \pi l = \text{const}, \tag{6}$$

where

$$l = \frac{d}{\lambda}; \tag{7}$$

λ is the wavelength of the accelerating voltage.

The energy gain of a resonance electron at $\nu > 1$ is not a function of $\nu > 1$ is not a function of ν and is determined by the formula

$$(\Delta W)_\nu = eV_a \frac{\sin l\pi}{l\pi} \cos\varphi_s = eV_s = \text{const}, \tag{8}$$

where

$$V_s = \bar{V}_a \frac{\sin l\pi}{l\pi} \cos\varphi_s. \tag{9}$$

The value V_s is called the equilibrium or resonance accelerating voltage. A graph of the function $(\sin l\pi)/l\pi$ is shown in Fig. 2.

The revolution period of an electron with total energy E in a magnetic field with strength H equals

$$T = \frac{2\pi E}{ecH} \quad (E = W + E_0, \quad E_0 = m_0 c^2). \tag{10}$$

Inasmuch as the energy of a resonance electron after passing through the resonant cavity is increased each time by the same value $\Delta W = eV_s$ (if $\nu > 1$), the revolution period of the electron is also increased each time by the same value

$$\Delta T = T_{\nu+1} - T_\nu = \frac{2\pi V_s}{cH} \qquad (\nu = 2, 3, \ldots). \tag{11}$$

This fact lies at the base of the microtron concept. In fact, it follows from (11) that although the revolution period of the electron being accelerated increases from revolution to revolution, while the period of the accelerating field does not vary, the resonance acceleration of an electron may be accomplished just the same at constant phase, in accordance with Condition (2). For this it is necessary that

$$\Delta T = bT_y, \tag{12}$$

where b is a constant non-zero integer. In this case conditions may be created at which the revolution period T_ν of an electron in any orbit with $\nu > 1$ will be a multiple of the period T_y of the HF accelerating field, on the strength of which Condition (2) will be satisfied also.

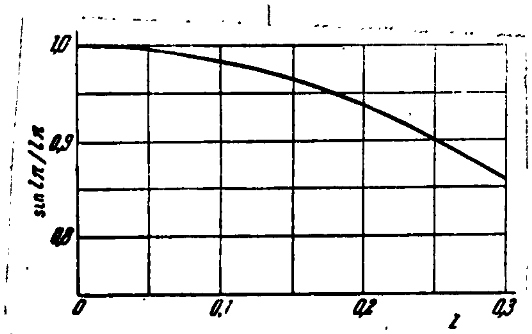

Fig. 2. The transit-time factor as a function of the dimensionless length of the accelerating slit.

Conditions (11) and (12) give us

$$\frac{2\pi V_s}{cH} = bT_y. \tag{13}$$

Condition (13) is the fundamental condition of resonance acceleration in a microtron and must be fulfilled at any of the various applicable operating conditions of this accelerator. However, it is only a necessary condition, not a sufficient one. Let us take the following as the second condition: Let

$$T_2 = mT_y, \tag{14}$$

where m is an integer (as will be shown below, m may not be less than 2*).

When Conditions (13) and (14) are fulfilled jointly, the revolution period in any period starting from the second will be determined by the expression

$$T_\nu = [m + (\nu - 2)\, b]\, T_y. \tag{15}$$

Therefore, the multiplicity factor ("resonance multiplicity"), i.e., the value $g_\nu = T_\nu/T_y$, varies from revolution to revolution:

$$g_\nu = m + (\nu - 2)\, b. \tag{16}$$

This is illustrated by Fig. 3, which shows the individual case: $m = 3$, $b = 1$.

Let us denote the kinetic energy W_1 of an electron after the first transit through the resonant cavity by $c_1 E_0$:

$$W_1 = W_{inj} + \Delta W_1 \equiv c_1 E_0, \tag{17}$$

---

*The second condition is usually written in this form: $T_1 = aT_y$, where a is an integer. However, if the revolution period T_1 is understood as time interval from one moment of intersecting the middle of the accelerating slit to the next, the, strictly speaking, the usual formula $T_1 = 2\pi E_1/ecH$ is inaccurate, since in the segment AB from the middle of the slit to the exit from the HF field the velocity of the electron is essentially unchanged; therefore, the mean velocity of the electron in the segment AB differs from that of the electron in its circular orbit beyond the limits of the resonant cavity. It stands to reason that the actual value of T_1 under real conditions differs little from $2\pi E_1/ecH$ and, as a result, from aT_y. An error of this kind may be ignored for the second orbit, since the velocity of the electron becomes, for all practical purposes, constant ($v \simeq c$).

where W_{inj} is kinetic energy of electrons to be injected into the resonant cavity.

Also let

$$\Delta W = eV_s \equiv c_2 E_0. \tag{18}$$

Then Condition (14), taking (10) into account, is rewritten as follows:

$$T_2 = \frac{2\pi E_0}{ecH}(1 + c_1 + c_2) = mT_y. \tag{19}$$

Using the expression of T_y from (13), we obtain on the basis of (18) and (19)

$$\frac{m}{b} - 1 = \frac{1 + c_1}{c_2}. \tag{20}$$

This relationship, as is (13), is the condition of resonance acceleration in a microtron written in the most general form. Since the minimum value of b is equal to zero, and c_1 and c_2 are positive numbers, it follows from (20) that $m_{min} = 2$.

Condition (20) may be fulfilled in many ways, i.e., the most diverse operating conditions are possible for the microtron [8,9]; for example, m = 2, b = 1 may be selected; then $c_1 = c_2 - 1$, therefore, only values of $c_2 > 1$ will be suitable (i.e., $V_s > 511$ kv), and the magnitude of W_1, which is expressed in kev, must by less by 511 than V_s in kv. If m = 3, b = 1 is chosen, then relationship (20) takes the form: $1 + c_1 = 2c_2$. Therefore, for example, these conditions are possible $c_1 = c_2 = 1$; $c_1 = 1, 4$, $c_2 = 1, 2$; $c_1 = 0.8$, $c_2 = 0.9$, etc.

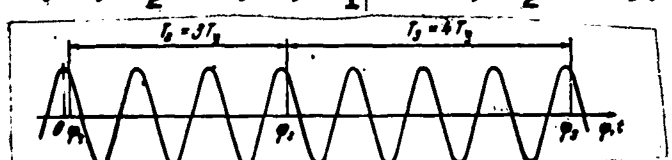

Fig. 3. Change in resonance multiplicity during the transition of a resonance electron from the second to third orbit.

In practice, b = 1 in all working microtrons, since in this case, as is apparent from (13), the chosen values of V_s and T_y correspond to the highest value of H in a microtron. This, in turn, indicates the possibility of obtaining the highest electron energy at a given diameter of the electromagnet pole.

Therefore, we shall examine only the case b = 1.

As is apparent from the above examples, the regime at which b = 1 and m = 2 may be accomplished only under special conditions (which will be treated in more detail later); in practice, this regime is still not used. The most widely used regime is that at which b = 1 and m = = 3. Therefore, it is usually called the basic regime of the microtron.

Condition (13) at b = 1 may be rewritten in the form of the following working formula:

$$H\lambda = \frac{2\pi E_0}{e} c_2 = 10{,}697 c_2 \text{ [kilo-oersted]}. \tag{21}$$

The second resonance condition at b = 1 has the form

$$m - 1 = \frac{1 + c_1}{c_2}. \tag{22}$$

Let H_c be that value of the magnetic-field strength (cyclotron field) at which the revolution period of a slow electron would equal the given time value T_y. Then

$$H_c = \frac{2\pi E_0}{ecT_y} = \frac{2\pi E_0}{e\lambda} = \frac{10{,}697}{\lambda} \text{ [kilo-oersted]} \tag{23}$$

Thus the coefficient c_2 is expressed through H_c:

$$c_2 = \frac{H}{H_c}. \tag{24}$$

From (10), (13), (8) and (15):

$$E_\nu = \frac{T_\nu}{T_\gamma}\Delta W = (m+\nu-2)\,\Delta W = E_0(m+\nu-2)\,c_2 \qquad (\nu = 2, 3, \ldots). \tag{25}$$

In his work Moroz [10] examines the possibility of using "softened acceleration conditions" in the microtron. It is shown that the "resonance portion of the energy" (eV_s), determined by Condition (13), may be imparted to an electron not in one transit through the accelerating slit, but in several successive transits, which form a cycle. The advantage of this acceleration regime is the possibility of increasing the working value of H by a factor of 1.4 to 1.7. However, the fraction of capturable electrons in acceleration is sharply decreased in comparison with the usual in the microtron, and the beam current falls correspondingly. In addition, when the microtron operates under "softened conditions," a very high stability in the values H, V_a and λ is required.

Let us pause briefly on the problem of selecting parameters in designing the microtron. The designer aims at as high a resonance strength of the magnetic field as possible, because the higher H, the lower the diameter of the electromagnet pole will be and, therefore, the more compact the accelerator will be. As is apparent from (21), in order to increase the magnitude of H, it is necessary to select the highest possible value of the ratio c_2/λ, i.e., to select a high value of V_a and a low value of λ. At the present time the lower limit of the wavelength of the field in the resonant cavity is determined by the fact that when λ is decreased the dimensions of the resonant cavity are decreased and, therefore, the length of the accelerating slit is decreased and the amplitude E_a of the electrical-field strength in the resonant cavity is increased at a given value of V_a ($E_a = V_a/d$).

The highest allowable value of E_a at which there will be no breakdowns in the resonant cavity is to a considerable degree a function of the state of the emitting surfaces at the edges of the apertures in the resonant cavity. It may be taken that $E_{a,max} \approx 1$ Mv/cm. Then, for example, at $V_a = 560$ kv and $\underline{1} = d/\lambda = 0.1$ the minimum wavelength $E_{a,\,min} \simeq 5.6$ cm.

Let us note that with a decrease in wavelength there is an additional advantage; a reduction of the diameter of the resonant cavity allows a decrease in the height of the interpolar gap of the microtron electromagnet and thereby an increase in the diameter of the region within which $H(r)$ = const with a given degree of accuracy.

It stands to reason that in selecting the value of λ, the data on how the power and cost of an HF generator capable of creating an electrical field with the required strength in the resonant cavity is a function of λ should be taken into account.

In most working microtrons an accelerating field with $\lambda \sim 10$ cm is used. If $c_2 = 1$ (i.e., $V_a \sim 560$ kv) and $\lambda = 10$ cm are taken, then according to (21), $H \simeq 1.0$ kilo-oersted. This example shows that in microtrons the master magnetic field should have very low strength, much lower than those values of H which are easily obtained in the interpolar gap of an electromagnet with an iron core even when the magnetic quality of the iron is not high. For comparison, let us show that a magnetic field with $H \sim 15$ to 20 kilo-oersted and over is usually used in cyclotrons and in betatrons $H_{orb} \sim 4$ to 9 kilo oersted.

Due to the low value of H, the pole of the microtron magnet has a diameter which is considerably larger than, for example, that of the betatron, which is designed to accelerate electrons to the same energy. However, there are certain advantages connected with this low value of H: the design of the electromagnet is very simple and the weight of the magnet is relatively low.

A number of authors have put forth various suggestions for increasing the working value of H and thereby making the microtron more compact. These ideas will be described below.

A microtron with a given value of H can operate at various frequencies of the accelerating field. All possible variants of the working conditions in this case, as is apparent from (21), will be subordinate to the condition c_2/λ = const. This means that then the wavelength is decreased, it is necessary to decrease V_a enough so that a considerably lower power is required by the generator supplying the resonant cavity. In some cases this fact was decisive in selecting the operating conditions of the microtron. It should, however, be forne in mind that it is desirable to use as high as possible values of c_2 and correspondingly V_a, since in this case the assigned final energy of the electrons will be attained at the lowest number of their transits through the resonant cavity, and electron losses in acceleration will be minimum.

It is necessary to select the parameter m also for the microtron being designed. Knowing m, c_1 may be caluclated from (22). A further problem is that of ensuring those conditions of electron injection at which the required value of c_1 will be obtained. The methods for attaining these conditions depend upon the type of injection.

Finally, the value of the equilibrium phase φ_s is chosen (usually $\varphi_s \approx$ 13 to 20°, see below) and, knowing the length d of the accelerating field, V_a is calculated by Formula (9). Experiment shows that the value of V_a found by (9) should be increased by 5 to 7%, in order to take into account the slackening of the HF field beyond the geometrical length of the accelerating slit and the curvature of the path of the electron in the resonant cavity.

2. The injection of electrons into the microtron

Five types of injection have been tried in practice up to the present time. Although the oldest method is still the most widely used, it will undoubtedly be replaced by new, more modern methods of injection in most cases.

Let us examine all these methods.

a) Injection using autoelectronic emission from the metal of the resonant cavity. This version of injection let us call autoelectronic injection.

The resonant cavity usually used in the microtron is shown schematically in Fig. 4. During operation of the resonant cavity, the highest electronic-field strength occurs at the surfaces of the annular zones, denoted in Fig. 4 by the letters A and B. These annular metallic surfaces are sources of an intensive electron stream, part of which may be used for furtheracceleration in the microtron*. Inasmuch as injection in the microtron must be unilateral, it is necessary to take measures to increase the intensity of autoelectronic emission from one annular zone (from zone A in Fig. 4.) and to lower substantially the emission from the other zone. If bitateral autoelectronic emission is allowed, then the result will be increased load on the resonant cavity by electrons which are not useable later on, and the increase will correspond to the increase in power required by the resonant cavity.

* It should be noted that the assumption about the autoelectronic nature of electron emission from the packing of the resonant cavity has so far not been proven by direct experiment. This observable electron emission is probably the result of a combination of several processes--autoelectronic, secondary and photoemission [5].

Unilateral emission is attained by the appropriate processing of the metal surface, and also by choosing suitable metals. Emission is sharply increased, for example, with oxidized or dull surfaces and greatly decreased when the surfaces are polished, carefully cleaned, or gilded. In some microtron resonant cavities an aluminum collar is placed on one of the resonant-cavity cones, in order to increase autoelectronic emission.

As is known, the electron current I in autoelectronic emission is very much dependent upon the strength of the field near the cathode surface. If the Fowler-Nordheim formula is used and it is assumed that the electrical field in the resonant cavity varies according to the law $E(t) = E_a \cos \omega_y t$, the following relationship may be obtained:

$$I = I_0 \cos^2 \omega_y t \cdot \exp\left(-\frac{B}{\cos \omega_y t}\right), \qquad (26)$$

where I_0 and B are constants, proportional to the magnitude of E and functions of the properties of the emitting surface.

The graph of $I(\omega_y t)$, according to Formula (26) is shown in Fig. 5. As is apparent from this graph, a pulse source acts during autoelectronic emission, wherein the emission current, in practice, differs from zero only at emission phases (φ_{em}) from about -52° to +52°.

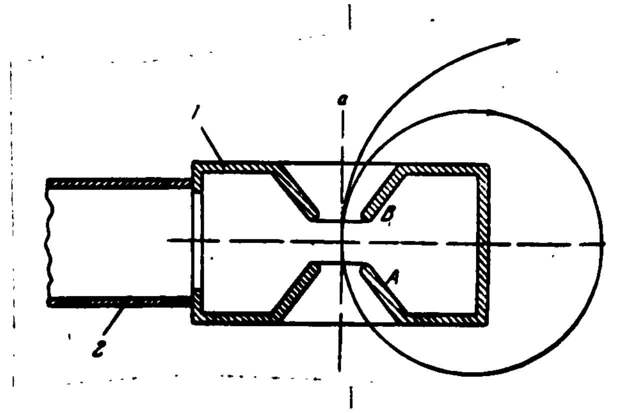

Fig. 4. Diagram of a toroidal resonant cavity.
1--resonant cavity (body of rotation about the a-axis); 2--waveguide.

In this version of injection $W_{inj} = 0$, so that according to (17)

$$c_1 E_0 = \Delta W_1. \tag{27}$$

From (22) we obtain

$$\Delta W_1 = (m-1) V_s - 511 \text{ [kev, kv]}. \tag{28}$$

In autoelectronic injection c_1 may not be larger than c_2, and usually $c_1 \simeq c_2$. If $c_1 = c_2$, resonance conditions (21) and (22) are simplified and take a form which is widely used in the literature:

$$eV_s = \frac{E_0}{m-2}, \tag{29}$$

$$H\lambda = \frac{10{,}697}{m-2}. \tag{30}$$

According to these formulas, m may not be less than 3, and V_s may not be greater than 511 kv and only the following values may be used: 511, 255.5, 170.3, etc.

If, in reality, the equality $c_1 = c_2$ is fulfilled only approximately, then Formulas (29) and (30) will be approximate also. In addition, in the case of $c_1 \neq c_2$, conditions with m = 2 are not excluded.

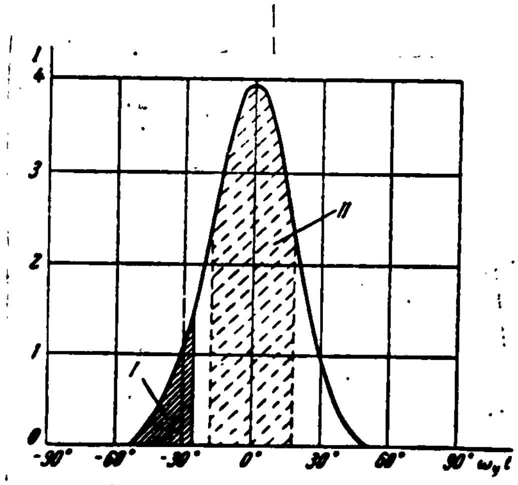

Fig. 5. Autoelectronic emission current (in relative units) as a function of the phase of the HF field.

Knowing the parameters V_a, φ_s and $\underline{d}$ of any real microtron, V_s may be found by (9) and the required value of ΔW_1 may be calculated by (28). On the other hand, the energy gain of an electron in a HF field with given values of V_a and $\underline{l} = d/\lambda$ is a function of the emission phase of this electron and may be caluclated by a well known scheme [11, 5]. Fig. 6 shows a graph of $\Delta W_1(\varphi_{em})$ calculated for the following conditions [12]: $V_a = 280$ kv, $\underline{l} = 0.066$. Using this graph, let us examine the following example. Assume that in a given microtron m = 4 and $c_2 = 0.5$ (c_2 corresponds to V_s = 255.5 kv; therefore, according to (9), ($\varphi_s \simeq 24°$). Then Condition (28) requires that ΔW_1 equal 255.5 kev. This energy gain is obtained by an electron with emission phase $\varphi_{em} \simeq -60°$ (see Fig. 6). It may happen that this electron has phase $\varphi^{(2)} = \varphi_s$; in this case it will be a resonance electron. However, fulfilling the condition $\varphi^{(2)} = \varphi_s$ is not obligatory, since nonresonance electrons may be accelerated in a microtron if their energy and initial phase $\varphi^{(2)}$ are sufficiently close to the energy and phase of a resonance electron (see Section 3). Therefore, in the microtron in question not only electrons with $\varphi_{em} = -60°$ will be stably accelerated, but also electrons emitted at other values of φ_{em}. A calculation made for this microtron [12] showed that only electrons whose emission phase lay within the limits of from -60 to -26° could pass through the resonant cavity eight times and be accelerated to the required energy of 2.044 Mev.

Using the graph of $I(\varphi_{em})$ (see Fig. 5), it is easy to determine, for example, by plane geometry, that the electron current corresponding to this suitable mission-phase region (the measure of this current is the shaded area I in Fig. 5) is in all 7% of the total current of the electrons which passed through the resonant cavity and entered the first orbit. In this a divergent electron beam leaves the resonant cavity; inasmuch as the uniform magnetic field of the microtron does not create axial focusing forces, only about 10% of the electrons injected in the first orbit strike the port port of the resonant cavity in the second orbit. Thus only about 0.7% of those electrons which were in the first orbit reach the second. This result is in good agreement with a well known fact observed in microtrons with autoelectronic injection: very high electron losses (often over 99%) occur during transition from the first orbit to the second. As a result, these microtrons are inefficient accelerators, with an output beam current of less than 1 μa (average current with respect to time).

A highly effective method of increasing the "utilization factor" of autoelectronic emission might be to increase the amplitude of the electrical field in the resonant cavity. For example, if E_a were doubled, then the emission current would be increased, according to (26), by a factor of 30, in the first place. In the second place, owing to the change in the shape of the curve in Fig. 6, the range of suitable emission phases would be shifted to the right in Fig. 5, which would lead to an increase in the relative magnitude of the shaded area by a factor of 4.4 [12] and the beam current at the output of this microtron would be increased by a factor of 130.

In practice, however, there are great difficulties connected with increasing the value of E_a. In order to increase E_a, it necessary to either increase V_a in this resonant cavity, or to use another resonant cavity, with a shorter acceleration gap. The maximum value of V_a has already been selected from other considerations. Therefore, the length d must be decreased. However, this increases the danger of resonant-cavity breakdown and its parameters are deoptimized; the Q-factor of the resonant cavity and its shunt resistance are decreased, as a result of which high power is required in order to obtain the same value of V_a. Usually, at $\lambda = 10$ cm and $V_a \sim 560$ kv, the length _d_ is not less than 8 mm [13].

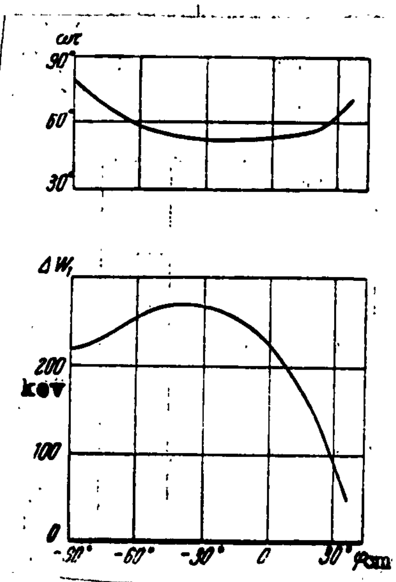

Fig. 6. Electron energy after the first transit through the resonant cavity and the transit phase angle as a function of the emission phase of the electron. V_a = 280 kv, _l_ = 0.066, initial electron velocity v_0=0.

By calculation one may establish what the conditions must be at which the range of suitable emission phases will be distributed symmetrically relative to the autoelectronic-current peak (Fig. 5). For this it is necessary to calculate the length _d_ of the accelerating slit such that the suitable emission phases are grouped near the phase $\varphi_{em} = 0$. Using the graph in Fig. 5 it is easy to calculate that in this case (if the same width of the range of suitable emission phases is taken, i.e., 35°) the relative magnitude of the shaded area would equal not 7, but 70% (area II).

Calculations of the optimum length of the accelerating slit have been published recently [14, 15]. Two somewhat different approaches to this calculation have been put forth. Let us examine both versions briefly.

1. The problem is set up as follows [14]. An electron is emitted when the $\varphi_{em} = 0$, when the autoelectronic-emission current is maximum, and acquire maximum energy ΔW_1 in transit through the resonant cavity. This means that the phase φ_{ex}, at which the electron leaves the resonant cavity, must equal 90°. It is required that this electron, having made one revolution in its orbit, strike the resonant cavity at phase $\varphi^{(2)} = \varphi_s$, then at phase $\varphi^{(3)} = \varphi_s$, etc. That length of the accelerating slit at which this requirement is satisfied will be considered optimum. It happens that at given values of φ_s, λ and m, this requirement may be satisfied only at a single value of V_a, and the same thing holds for d_0. Table I gives the results of Paulin's calculations [14]; $\varphi_s = 18°$, $b = 1$.

Table I

m	V_a, Мв	$\lambda \sim 10$ см			$\lambda \sim 3$ см		
		H, [illegible]	d_0, мм	D_1, мм	H, [illegible]	d_0, мм	D_1, мм
2	2,369	4398	20,7	27,7	14660	6,2	8,3
3	0,427	828	12,8	42,8	2761	3,6	12,8
4	0,238	473	10,1	53,0	1573	3,0	15,9
5	0,165	325	8,6	62,6	1083	2,6	18,8

The following conclusions are made from these results. In microtrons operating at $\lambda \sim 3$, the length of the accelerating slit considerably exceeds the optimum value of do given by the calculation (for example, at m = 4 in working microtrons $d \geq 4.5$ mm, whereas $d_0 = 3$ mm). This may explain the low utilization factor of autoelectronic emission. For microtrons working at $\lambda \sim 10$, it is entirely possible to build a resonant cavity having an acceleration gap of optimum length, if $m > 2$. However, the resonance strength of the magnetic field happens to be very low, and the accelerator will not be compact.

Another fact is even more essential. It is found that the value of E_a found in this parameter calculation is lower than usual (e.g., at λ 10 cm and $m = 3$, $E_a = 334$ kv/cm). This leads to a substantial lowering of the electron current of autoelectronic emission.

Thus it may be concluded that optimum length of the accelerating slit in the above sense should not be the aim, but rather its length should be as short as possible. Loss in emission current connected with the fact that the maximum attainable amplitude of the electrical field is chosen will, apparently, be much greater than the loss due to deoptimizing the distribution of the range of suitable emission phases relative to the phase $\varphi_{em} = 0$.

The case of $m = 2$ is interesting. It corresponds to an unusually high value of $H (\sim 4.4$ kilo-oersted) and $E_a \simeq 1.14$ Mv/cm. Note that in this case $c_1 \simeq 2.7$ and $c_2 \simeq 3.7$, which is easily calculated. When the path of the electron is the usual one, this version is not feasible, because the length of the accelerating slit is too great in comparison with the diameter D_1 of the first orbit. The author assumes that acceleration may be accomplished at $H \sim 4.4$ kilo-oersted, electrons being given out from the resonant cavity through the corresponding aperature (Fig. 7). No calculations are given however.

2. In the second version of the calculation of the optimum length of the accelerating slit, the problem is set up as follows [15]. An electron is emitted at phase $\varphi_{em} = 0$ and leaves the resonant cavity at phase φ_{ex}, regarding the magnitude of which no conditions are given. It is necessary that the magnitudes of V_a and d_0 be such that this electron, having made one revolution in its orbit, strikes the resonant cavity at phase $\varphi^{(2)} = \varphi_s$. In addition, a second requirement is made: The revolution period of this electron must be exactly equal to

an integral multiple of the periods of the accelerating field (see footnote on page 7). Note that the advancement of the second requirement is hardly advantageous; it is sufficient to fulfill only the first one. Table II shows the results of the calculation; $a = \frac{T_1}{T_y}$, $l_0 = d_0/\lambda$.

Table II

a	$\varphi_s = 18°$: V_a, kv	l_0	φ ex	$\varphi_s = 24°$: V_a, kv	l_0	φ ex
2	531	0,042	25,6°	578	0,0583	34,1°
3	271	0,0296	23,3°	283	0,0401	31,2°

As is apparent from the data in the table, the accelerating slit must have a shorter length than in working microtrons. For example, at a = 2 and λ=10 cm, d_0 = 4.2 mm. It is possible that freedom from breakdown could be attained in a resonant cavity with d = 4.2 mm at V_a = 531 kv; its Q-factor would be lower than usual and the power required would be higher than usual, however, this would be worth the increase in beam current at the output of the microtron.

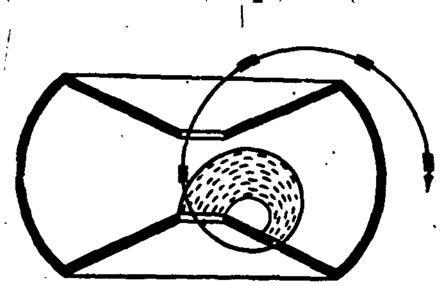

Fig. 7. Electron path shown for an increase in the upper limit of strength of the master magnetic field.

In the second version of the calculation, as is in the first, the working value of V_a (and correspondingly the value of H, if the equilibrium phase φ_s is assigned) is found to be rigidly fixed, and deviation from the required value must lead to a decrease in beam current. Unfortunately, to what extent the calculated parameters agree with experimental ones has not been checked.

In a working microtron the resonant cavity has a fixed dimension d, and the conditions corresponding to the maximum beam current of accelerated electrons are chosen as follows: V_a is varied and the optimum value of H is selected for each value of V_a; as a result, opt V_a and opt H are found (see Section 3). From these values, it would be possible to calculate those values of φ_s, c_1 and c_2 which are optimum for the given microtron, and also to establish where the optimum range of suitable emission phases is distributed relative to the phase $\varphi_{em} = 0$.

In his work, Reich [6] describes the results of an experimental study of some processes which occur in autoelectronic injection. In order to trace the path of electrons emitted from a definite point on the surface of the conic packing in the resonant cavity, the following simple method was used. An artificial center of emission was created on the well polished edge of the port in the resonant cavity in the form of a speck of aquadag. Data on the shape of the path of electrons emitted from this point were obtained using movable slits and a screen covered with luminophor. Thus it was established that only two extremely small areas of the emitting surface deliver those electrons which later on may pass through the resonant cavity the resonant cavity the required number of time without hindrance. The dimensions of these areas are: $x \simeq 0.3$ mm, $y \simeq 3$mm (Fig. 8). Area a may be called the external emission zone, and area b the internal emission zone. Experiments show clearly that the two electron beams emitted by the external and internal emission zones later on form two entirely separate orbital systems.

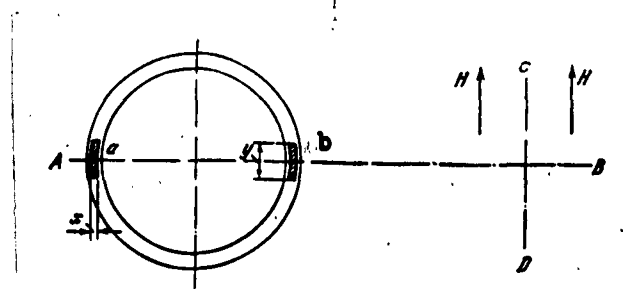

Fig. 8. Diagram of the working emission zones (a, b) on the edge of the port in the resonant cavity. AB--orbital plane, CD--axis of symmetry of the magnetic field.

The practical conclusion from these observations is that it is necessary to take measures to supress autoelectronic emission from the entire surface of the port in the resonant cavity lying beyond the areas a and b; thus the power required by the resonant cavity will be considerably lowered. The measures given by Reich [6] boil down to the fact that the brass conical packing in the resonant cavity was well polished. Then a thin layer of aquadag is applied to the working emission zone. "Molding" of this coating occurs during breakdowns in the resonant cavity, formed when V_a is increased slowly. After cessation of breakdowns, this emission zone gives a stable electron current of from 100 to 200 μa (pulse) on the third orbit*.

In other microtrons with autoelectronic injection, the beam current in the last orbit is often several times greater than that obtained in Reich's work [6]: it is ~ 1 ma (pulse). An even higher current (up to 7 ma (pulse)) was obtained using this same type of injection in the work of Kapitsa, et al. [7].

*A local electron emitter in the form of a point was also tried. It was found unadvantageous to use this source of autoelectronic emission [6].

Thus a microtron with autoelectronic injection with an electron energy of 5 to 6 Mev can provide a beam current which is entirely sufficient for conducting many physical studies. This microtron is distinguished by the simplest design.

b) Injection using a thermal cathode located inside the resonant cavity. Experiments with this type of injection are also described in Reich's work [6]. A tantalum wire 0.4 mm in diameter was used as the cathode. It was mounted in the gap of the resonant cavity approximately in the vertical plane and close to zone b (see Fig. 8). The cathode serves sufficiently long if it is not heated to excessively high temperatures. A stable current of 500 μa (pulse) was obtained in the third orbit. This value is apparently close to the maximum attainable in this type of injection (if an oxide cathode is not used), inasmuch as the area of the working zone of emission is very small, while the time interval in each cycle of the HF field, during which electron capture takes place under acceleration conditions, is in all about 0.1 T_y in the microtron.

The structure of the resonant cavity is more complicated than in autoelectronic injection. There are a few difficulties connected with the fact that the magnetic field of the cathode causes a noticeable vertical shift in the orbits; these difficulties have been overcome.

Inasmuch as in the type of injection now under examination it is not necessary to have the highest possible value of E_a in the resonant cavity, a resonant cavity with an accelerating slit having a greater length may be used. This leads to an improvement in the Q-factor of the resonant cavity.

As in autoelectronic injection, the limit $c_2 \leq 1$ at m = holds.

c) Injection using an electron gun. The electron gun, which may be used as an injector in the microtron, is subject to the following requirements: it must have extremely small dimensions, so as not to disturb the motion of electrons in the first orbit; electrons must pass in a gun of sufficiently high potential difference, in order that, having left the gun, they may hit the gap of the resonant cavity, in spite of the deflecting action of the magnetic field of the microtron; the electron gun must give a sufficiently intense electron beam. The last two requirements contradict the first, and it is not easy to find a satisfactory compromise solution. If it were possible to build a small electron gun which provided electrons with an energy of ~ 300 kev, the first requirement would be less rigid, since the gun could be installed in the "most free" place near the resonant cavity (Fig. 9). However, as an experiment in designing injectors for betatrons and synchrotrons shows, electrons with energies no greater than 80 to 100 kev may be obtained from miniature guns when they are pulse fed. At this energy, the radius of curvature of the electron path in a magnetic field H $\simeq$ 1.2 kilo-oersted will be 8 to 9 mm in all. Therefore, the injector must be placed near the gap in the resonant cavity. Striking the accelerating field of the resonant cavity, the electron begins to acquire energy, and the radius of curvature of its path increases rapidly.

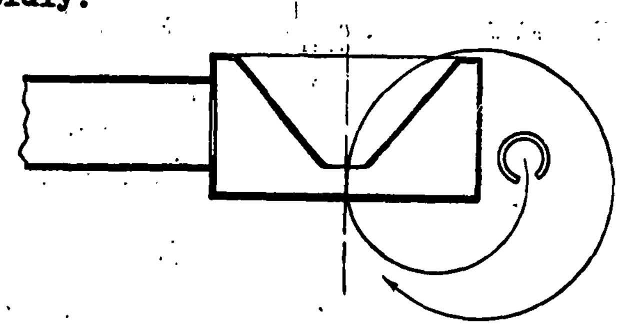

Fig. 9. A possible location of the injector at a high injection energy.

This type of injection is used in the 5.9-Mev microtron, and will be used in the 1.2-Gev, rigid-focusing synchrotron being built at the Lund University [16, 17]. The placement of the electron gun relative to the resonant cavity is shown in Fig. 10*. Negative pulses having an amplitude of 80 kv relative to the grounded anode strike the injector cathode, which is a tungsten filament. The emission current is ~ 500 ma (pulse); this beam enters the resonant cavity. In the 10th orbit the current is usually 20 ma (pulse). A dispersive cathode was alos used, which allowed the current to be increased by a factor of 2 to 2.5; however, the cathode life in this type of vacuum system is only a few hours.

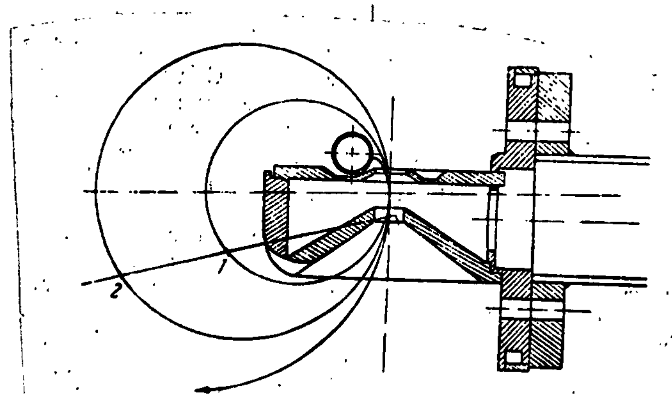

Fig. 10. Placement of injector in the Swedish microtron. A Faraday cup moves along the line 1--2; it is used to measure the beam current in various orbits.

The pulses supplied to the cathode must have flat-part duration of ~ 2 μsec, since the resonant cavity is fed by pulses with a duration of 2.7 μsec and part of this time is spent in starting oscillations in the resonant cavity up to a stationary value of V_a.

*This drawing and the basic parameters of this microtron were kindly sent to me by O. Vernholm.

As calculation showed [16], already at $W_{inj} \sim 60$ to 70 kev all electrons are stably accelerated whose phase is a range with a width of $\pm 25°$.

From the parameters of the given microtron ($H = 1.23$ Kilo-oersted, $\lambda \simeq 9.95$ cm, $b = 1$, $m = 3$) it may be determined that $c_2 = 1.143$, i.e., $\Delta W = 584$ kev, $c_1 = 2c_2 - 1 = 1.286$ and $\Delta W_1 = 577$ kev. A higher value of c_2 could be obtained only at a higher injection energy. However, even at $W_{inj} = 300$ kev, the value of c_2 would not exceed 1.576, so that at $\lambda = 9.95$ cm the resonance strength of the magnetic field would not be greater than 1.7 kilo-oersted.

d) Injection using a second resonant cavity. A resonant cavity operating at the same frequency as the main resonant cavity of the microtron may be used as a high-voltage electron gun [8]. The electron source may be either a separate thermal cathode (Fig. 11), or a properly processed surface of the resonant-cavity packing, which emits electrons by autoelectronic emission. As distinguished from autoelectronic injection, in this case the utilization factor of autoelectronic emission can be made very high. In fact, if a phase-shifting device is introduced into the feed circuit of the injection resonant cavity, then that phase shift between the oscillations in the injection and main resonant cavities at which the maximum portion of autoelectronic-emission electrons will be captured under acceleration conditions may be chosen experimentally. At this optimum phasing of the resonant cavities, the utilization factor of the autoelectronic emission will be 70%, if the phase angle of capture is taken equal to 35° (see Section 2a).

The electron current which can be given by this injection resonant cavity may be made entirely sufficient. According to the data [18], up to 0.9 a (pulse) at λ ~ 10 cm and up to 0.3 a (pulse) at λ ~3 cm may be obtained immediately after the resonant cavity.

So far only one attempt has been made to apply the injection resonant cavity in practice [19, 6]. Both resonant cavities were fed by a single magnetron. In addition to regulation of relative phase shift, it was also possible to regulate the amplitude of the voltage in the resonant cavities independently. The effective power of the magnetron was found to be insufficient, and the experiments were not concluded. In the future, part of the power which is usually scattered in the stabilizing load will probably be used in microtrons of this type to feed the injection resonant cavity (see Section 5b). A ferrite attenuator should be used instead of this load; it would divert energy to the injection resonant cavity [12].

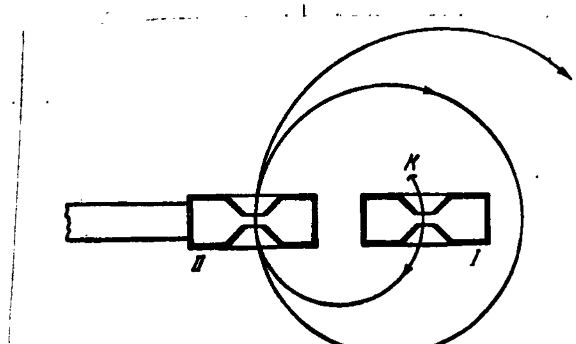

Fig. 11. Using a separate resonant cavity as the injector. K--thermal cathode; I--injection resonant cavity; II--main resonant cavity. The waveguide feeding I must be beyond the orbit plane.

Higher injection energy may be imparted to an electron by using an injection resonant cavity. It is found, however, that not all values of W_{inj} are permissible at a given value of H. This is due to the fact that the injection resonant cavity operates on the same wavelength as the main one, and therefore, it has the same dimensions.

Therefore, the radius of curvature of the path of electrons leaving the first resonant cavity and striking the gap of the second must be about twice the radius of the first orbit in an ordinary microtron (see, for example, Figs. 4 and 11), while radius of the first orbit in a two-resonator microtron must be four times greater than in an ordinary microtron. If in the latter at $\lambda = 10$ cm electrons with an energy of 511 kev freely bypass the resonant cavity at $H = 1.07$ kilo-oersted (since the diameter of the orbit $D_1 = 5.52$ cm, and the radius of a toroidal resonant cavity $R_{res} = (0.3 \text{ to } 0.35)\ \lambda = 3 \text{ to } 3.5$ cm), then, in a two-resonator accelerator, and electron with $W_{inj} = 511$ may go from the first resonant cavity to the second only at $H \leq 740$ oersted. If $H = 535$ oersted, then $c_2 = 0.5$, $m = 6$ is possible. In the first orbit a resonance electron will have an energy of 766.5 kev (the corresponding magnetic rigidity $G = 3906$ oersted·cm), and the diameter of this orbit will equal 14.6 cm; this is barely enough to bypass the injection resonant cavity. Another possible set of conditions are [18]: $W_{inj} = 255.5$ kev, $c_2 = 0.5$, $m = 5$. In both of these cases, a low magnetic-field strength must be used, in spite of the relatively high values of W_{inj}. Only at very high values of W_{inj} is it possible to use conditions with a high value of H. For example, in very compact resonant cavities($R_{res} = 0.3\ \lambda$) the following conditions are possible: $W_{inj} \simeq 1.53$ Mev, $m = 4$, $c_2 = 2$.

An injector in the form of an additional resonant cavity has still another advantage over the electron-gun injector: it gives very short clusters of electrons with a reperition rate equal to the oscillation frequency of the field in the resonant cavities; when the relative phasing of the resonant cavities is correct, for all practical purposes only "useful" electrons will be injected into the main resonant cavity, while many "useless" electrons (uncapturable under accelera-tion conditions) will reach the main resonant cavity when an electron gun is used, which works continuously in the course of its operating period. This leads to an increase in the power required by the reson-ant cavity.

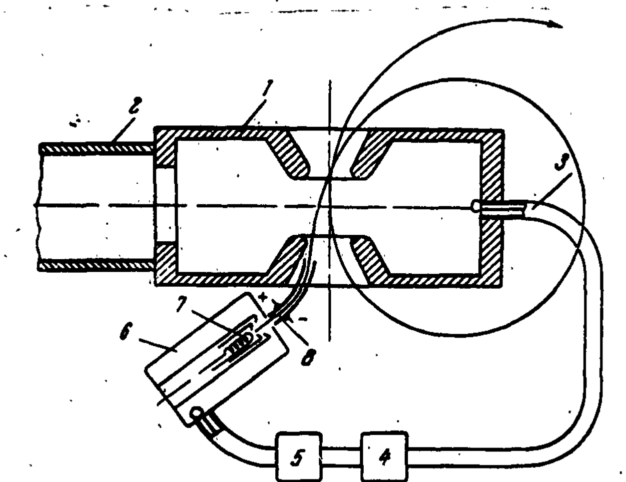

Fig. 12. An injector in the form of a coaxial resonant cavity. 1--main resonant cavity; 2--waveguide; 3--coaxial cable for feeding the injection resonant cavity; 4--phase changer; 5--attenuator; 6--injection resonant cavity; 7--electron gun; 8--electrostatic deflector (inflector).

Still another version of the device and placement of the injec-tion resonant cavity is possible (20). This may be in the form of a quarter-wave coaxial resonant cavity (Fig. 12). Its parameters are calculated so that a good grouping of electrons in the cluster is obrained. When locating the bunching resonant cavity (Fig. 12) it is necessary to change the sign of the curvature of the path of elec-trons in the section between the two resonant cavities. It is sug-gested that an electrostatic deflection device be used for this.

e) <u>Injection using a thermal cathode according to the method of S. P. Kapitsa, V. P. Bykov and V. N. Melekhin</u>. Some interesting n new suggestions are put forth in a recent article by these authors [7].

According to these suggestions, injection conditions are changed substantially and it becomes possible to increase the beam current of accelerated electrons considerably. The traditional resonant cavity of the microtron is replaced by a cylindrical resonant cavity, in which oscillations of the E_{010} type are excited. The thermal cathode is installed at a precisely calculated distance from the axis of the resonant cavity on its front wall in the orbit plane. When calculating the path of thermal electrons, the magnetic field, as well as the high-frequency fields (the electrical and magnetic fields inside the resonant cavity), is assumed constant. Fig. 13 shows one of the calculated electron paths, corresponding to an emission phase of 0°. When the length of the resonant cavity is fixed, various values of c_2 correspond to various cathode positions. When $\underline{l} = 0.163$, the possible values of c_2 are between 1 and 1.2.

An experimental study of this type of injection was made in a microtron with a pole diameter of 70 cm and an interpolar gap of 11 cm. The cylindrical resonant cavity had a diameter 2R = 7.66 cm (this corresponds to $\lambda = 10$ cm) and a length d = 1.63 cm. The lanthanum boride cathode, which can be heated to 1600° C, emitting-surface area of about 1 to 2 mm^2. The center of this area was at a distance of 1.75 cm from the axis of the resonant cavity. Under conditions with $c_2 =$ = 1.1 (V_s = 562 kv), the beam current in the 12th orbit reached 15 ma (pulse) at an electron energy of 6.8 Mev. From this energy value (using Formula (25)), it is found that m = 3. Therefore, according to (22), $c_1 = 1.2$. Thus a resonance electron moving within the resonant cavity must acquire an energy of 613 kev.

If $c_2 = 1.1$ and $\lambda = 10$ cm, then H ≅ 1.18 kilo-oersted (see (21)). Further, using (15) and assuming that at an energy of ~7 Mev the velocity of the electron equals the speed of light, it is found that the diameter of the 12th orbit equals $13\ \lambda/\pi = 414$ mm.

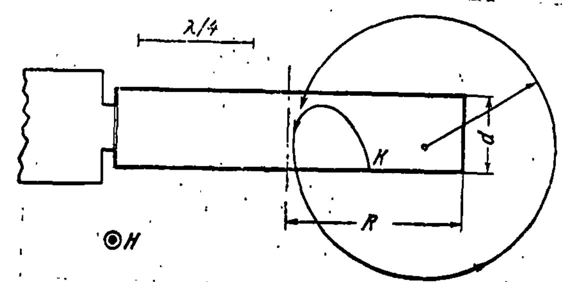

Fig. 13. The path of an electron when using a cylindrical resonant cavity (first version). K--thermal cathode.

Detailed calculations made on a digital computer showed that under acceleration conditions electrons are captured with an emission phase near $\varphi_{em} = 0$; the current of these electrons is ~ 1/30 of the total emission current. Experimental data supported this result.

In the work of Kapitsa, et al. [7], an even more successful method of using a thermal cathode in a cylindrical resonant cavity is suggested. If the thermal cathode is placed on the rear wall of the resonant cavity near its acis and an additional port is made in this wall in the orbit plane, then the electron path shown in Fig. 14 may be obtained. In this case the operating conditions may be $c_2 = 2$ to 2.5, i.e., the microtron is made considerably more compact. This type of injection was tested experimentally under the following conditions: The resonant cavity had a diameter of 7.66 cm and a length of 2.32 cm, the thermal cathode was placed at a distance of 3.2 mm from the axis of the resonant cavity. A H = 1.95 kilo-oersted, i.e., $c_2 = 1.823$ and $V_s \simeq 932$ kv, a current of 5 ma (pulse) was obtained in the 12th orbit, at an energy of 11.6 Mev. The diameter of the 12th orbit was 414 mm, as in the first working version of the microtron being described. This is natural, since in both cases the wavelength was the same.

Under the second set of conditions $c_1 = 2.646$, i.e., $W_1 = 1.352$ Mev. A thermal electron acquires this energy in two steps: in the section of the path from the thermal cathode to the exit of the resonant cavity (Fig. 14) and in the first traversing of the resonant cavity.

In this type of injection, under acceleration conditions, ~ 1/20 of the total emission current is captured.

The resonant cavities described here are distinguished by the great length of the accelerating slit: in the first case $\underline{l} = 0.163$, and in the second, $\underline{l} = 0.232$. However, detailed calculations of the paths showed that all electrons captured in acceleration can traverse the resonant cavity unhindered 12 times or more.

The cylindrical resonant cavity is inferior to the toroidal resonant cavity of the special shape usually used microtrons with respect to the magnitude of the shunt resistance in an accelerating gap of a given length. But since cylindrical resonant cavities with a high value of $\underline{l}$ were used, approximately the same power is required to excite this resonant cavity as that required in ordinary microtrons.

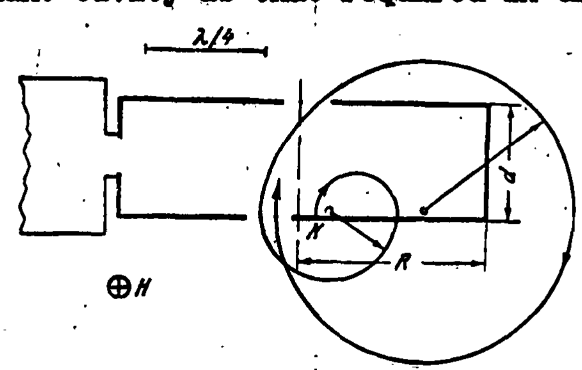

Fig. 14. The path of an electron when using a cylindrical resonant cavity (second version). K--thermal cathode.

Calculations show that it is advantageous to replace the cylindrical resonant cavity by a prismatic one. The use of this resonant cavity allows the height of the interpolar gap of the electromagnet to be decreased; in addition, the distribution of the electromagnetic field in this resonant cavity makes it possible choose that shape of the thermal-electron path at which the parameter c_2 is increased even more, i.e., the microtron will be even more compact.

Comparing this type of injection with that in which an electron gun is used, it is noted that in the second case somewhat higher beam currents at an energy of ~ 6 Mev were attained. A microtron with a thermal cathode and a cylindrical resonator has many advantages over all other versions described above. It is more compact, since it allows operation with very high values of c_2. Its design is more simple than that of a microtron with two resonant cavities or with electron-gun injection, and it allows the parameters to be varied considerably more freely, in design as well as in use. Very essential is the fact that all parameters of this microtron are precisely calculated, while in other types of injection, many must be chosen empirically.

Let us note that the two types of injection (thermal-cathode and electron-gun) make it possible to vary the beam current; this accomplished by regulating the filament current.

Still another type of injection (so far not tested experimentally) should be added to the five types described above. Aitken [21] has suggested that the annular source of electrons (thermal cathode or autoelectronic-emission source) be installed not at the edge of the accelerating slit, but in some plane which is approximately in the middle of this slit. The aim of this suggestion was to accomplish conditions with m = 2, b = 1, which, as was indicated in Section 1, corresponds to the condition $c_1 = c_2 - 1$. In this case a high value of c_2 may be taken (the author suggested the use of a cylindrical resonant cavity and $c_2 \simeq 2$); correspondingly, H is doubled in comparison with the usual value of ~1 kilo-oersted. The difficulty in accomplishing conditions with m = 2, b = 1 is that the diameter of the first orbit is too small and the electrons cannot get around the resonator. Therefore, it was suggested that an opening be made in both flat walls of the cavity in the orbit plane, in order to pass electrons. In a later work [22], it is stated that, as numberical calculations of of the motion of electrons in the first orbit showed, these openings will not serve the purpose. Therefore, another way of achieving conditions with m = 2, b = 1 is developed: the first orbit is given an elongated shape, owing to which the electrons pass around the resonant cavity unhindered. The required change in the shape of the orbit is attained by passing the electrons through two iron tubes, in the cavity of which $H \simeq 0$ (Fig. 15).

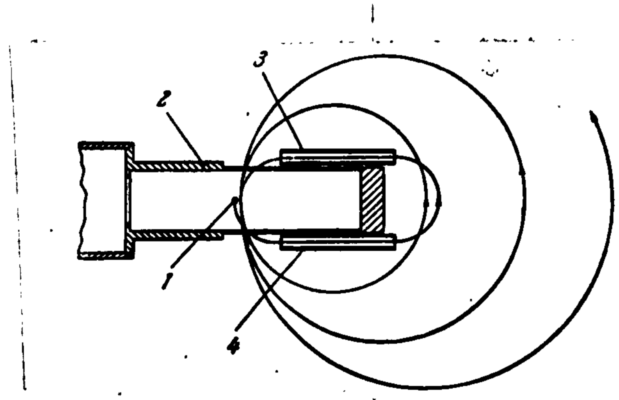

Fig. 15. Diagram of the placement of magnetic shields making it possible to increase the upper limit of the strength of the master magnetic field. 1--cathode; 2--cylindrical resonant cavity; 3,4--magnetic shields.

The length of the first orbit is increased such that the revolution period of the electron satisfies the condition $T_1 \simeq 2T_y$, rather than the condition $T_1 \simeq T_y$. In the second orbit $T_2 = 2T_y$.

Preliminary experiments have been made which gave encouraging results.

3. Phase stability in the microtron

The phenomenon of phase stability in cyclic accelerators, the discovery of which widened unusually the possibilities of accelerator technology, was first described by Veksler in the same article in which he put forth the idea of the microtron [1]. It was established that not only resonance electrons could be accelerated indefinitely in a microtron, but also many other electrons, under the condition that they not differ too much from resonance electrons in phase and energy. Automatic phasing consists of the fact that the phase of a nonresonance electron, varying from revolution to revolution, oscillates near the equilibrium phase φ_s.

The theory of phase oscillations in a microtron was later on treated in detail [2, 23, 8, 24, 25 (in chronological order)]. This theory answers a number of important practical questions. What is the optimum value of the equilibrium phase, i.e., what is the best value of V_a at a given value of V_s? What share of electrons injected into the resonant cavity by a continuous beam may be captured in acceleration at any value of φ_s? What is the energy spread of accelerated electrons? Within what limits may the energy of electrons moving in a given orbit of a microtron be varied?

Already in the first theoretical works, it was established that the microtron differs substantially, with respect to the nature of the change of phase of the particles to be accelerated, from all other accelerators based on the principle of phase stability. In the latter, the phase of a particle changes only by small jumps, i.e., the phase difference $\Delta\varphi_\nu = \varphi_{\nu+1} - \varphi_\nu$ is always small. This makes it possible to use a differential equation in the mathematical analysis of the phase equation. In the case of a microtron, $\Delta\varphi_\nu$ is not small and replacement of the difference by differentials may lead to large errors [26].

The phase equation of a microtron when b = 1 has the form [25]

$$\Delta^2\varphi_\nu - \frac{2\pi\cos\varphi_{\nu+1}}{\cos\varphi_s} = -2\pi. \tag{31}$$

The values φ_s and $-\varphi_s$ are particular steady-state solutions of this equation.

In the case of small phase oscillations, it may be assumed that

$$\varphi_\nu = \varphi_s + \eta_\nu, \quad |\eta_\nu| \ll \varphi_s. \tag{32}$$

Then (31) is transformed into a linear difference equation, the solution of which has the form

$$\left.\begin{aligned} \eta_\nu &= a\cos(\varepsilon\nu + \delta), \\ \cos\varepsilon &= 1 - \pi\tan\varphi_s, \end{aligned}\right\} \tag{33}$$

where a and δ are constants. From (33) it follows that an electron will be stably accelerated, i.e., phase stability will occur, if the tangent of the equilibrium phase is within the following limits:

$$0 < \tan(\varphi_s)_{\lim} = \frac{2}{\pi}, \tag{34}$$

hence for φ_s

$$0 < \varphi_s < 32{,}5^\circ. \tag{35}$$

Here again the essential difference between the microtron and all other accelerators with phase stability manifests itself with respect to phase motion; for the latter the upper limit of $|\varphi_s|$ equals 90°. Condition (35) means that in a microtron the value of V_a may exceed that of V_s only by a little more than 16% (since cos 32.5° = 0.843).

If the initial conditions (the phase and energy of electrons entering the accelerator) have a uniform distribution, then, using (33), it may be shown that the optimum value of φ_s is ~ 17.7°; at this value of φ_s the share of electrons capturable in acceleration will be maximum.

Fig. 16 shows the limiting curve $\psi_0 = \varphi_0 - \varphi_s$ at a given value of φ_s correspond to points lying within the limiting curve will be accelerated stably.

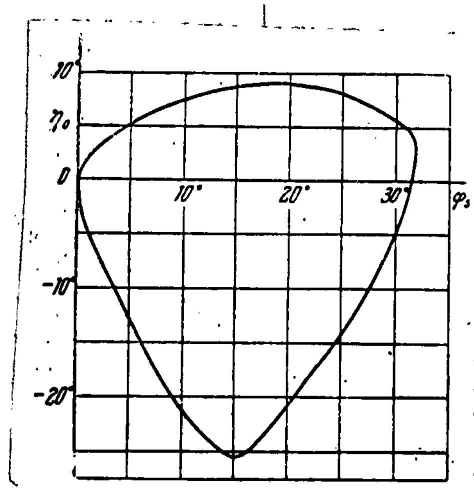

Fig. 16. Limiting curve $\psi_0(\varphi_s)$ for the case of small phase oscillations.

When $\varphi_s \simeq 17.7°$ the period ψ_p of phase oscillations, expressed by the number of transits of the accelerating slit, equals 4. When φ_s varies from 0 to 32.5°, the period ψ_p varies from ∞ to 2.

As was mentioned above, a is a constant in (33), i.e., small phase oscillations have a constant amplitude. Small phase oscillations are damped in other accelerators with phase stability.

When examining large phase oscillations, Equation (31) may be used as a recurring formula and the calculation made numerically. Several clever graphical methods have been developed [8, 24, 27] which allow $\varphi_{\nu+1}$ and $W_{\nu+1}$ to be determined from given values of the phase φ_ν and energy W_ν of an electron, after which $\varphi_{\nu+2}$ and $W_{\nu+2}$ may be found, etc. The graphical method suggested by Kisdi-Koszó [26, 27] is especially interesting, since he does not exclude those cases when one of the series of values of W, for example W_q, is smaller than the previous value W_{q-1} (i.e., the electron is decelerated in the resonant cavity).

When using one of these computational or graphical methods, one may obtain, in particular, a picture of the phase motion of an electron in coordinates $(\varphi_\nu, \Delta\varphi_\nu)$, the so-called phase orbits (Fig. 17). If the initial conditions are such that the mapping point is near the equilibrium point $(\varphi_s, 0)$, then later on the mapping point will move in jumps with respect to the corresponding phase orbit and its motion will be nearly periodic. The unclosed phase orbits indicate that the mapping point is not moving periodically, and the corresponding electron is not captured under conditions of unlimited acceleration.

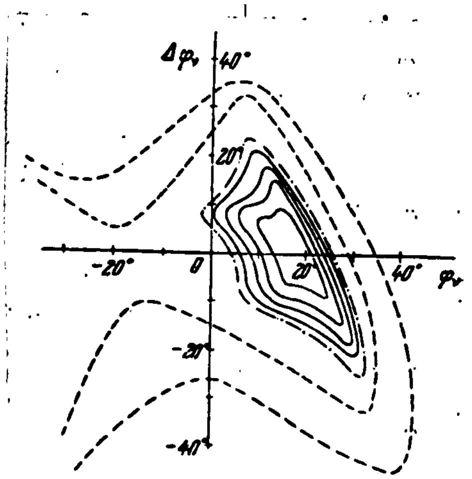

Fig. 17. The phase orbits of an electron when $\varphi_s = 17.7°$.

Calculation shows that if it is required that the electron traverse the resonant cavity a sufficient number of times, then, at $\varphi_s = 17.7°$, the phase angle of capture equals $\sim$ 29°. However, it should be remembered that in 5- to 6-Mev microtrons, an electron traverses the resonant cavity but 10 to 12 times; therefore, certain electrons reach the target for which, from the point of view of an indefinite number of accelerations, phase-stability conditions are not fulfilled [27]. On the other hand, data on the electron-beam current in various orbits which was obtained in several working microtrons [5, 13, 29] attests to the fact that during transition from one orbit to another, electron losses are negligible, starting with the second or third orbit (Fig. 18). This means that the phase angles of capture, calculated, for example, for the third and tenth orbits, will differ little from one another.

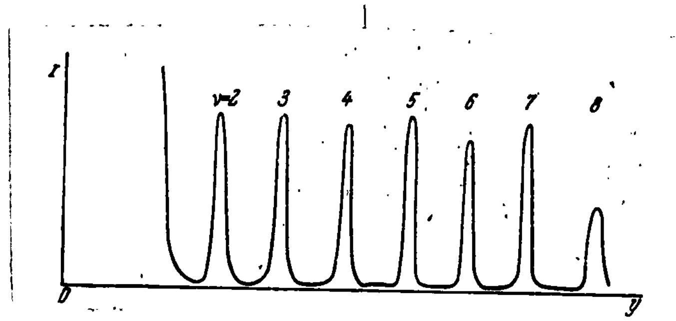

Fig. 18. The change in target current as the target moves along the total diameter of the orbit [5]. The point $y = 0$ coincides with the center of the accelerating slit.

Inasmuch as electrons with various input parameters are captured in acceleration, electrons with somewhat different energies may be found in each orbit, including the last. In order to calculate accurately the width of the energy spectrum of electrons in the last orbit, one must use the same "step by step" method which is used to calculate the trend of the phase change of the electron. Calculations show that the energy spectrum of electrons at the exit of the microtron is very narrow. For example, when $W = 4.09$ Mev, $H = 1.07$ kilo-oersted, $V_s = 511$ kv and $\varphi_s = 11.5°$, the total energy spread is 1.2% [27], i.e., $W \simeq (4.09 \pm 0.025)$ Mev*.

During this calculation, the duration φ_p of electron pulses at the exit of the microtron was determined simultaneously. The electron clusters have small expanse, and when $\lambda = 10$ ($f \simeq 3$ Gc, $T_y \simeq 3.3 \cdot 10^{-10}$ sec) φ_p will be about $3 \cdot 10^{-11}$ sec. These clusters follow each other with a frequency of 3 Gc at a duration of 1.5 to 2 μsec, after which the resonant cavity is switched off, for example, for 2 μsec.

In certain applications of the microtron, particularly when it is used to generate sub-millimeter electromagnetic waves [30, 18], it is desirable to obtain the shortest possible electron clusters. It is found [31] that, in theory under definite conditions it is possible to obtain great cluster compression in one of the orbits, for example, an angular length of the cluster of 30' may be obtained in the 8th orbit instead of the initial one of 8°.

The successful application of a small microtron for generating oscillations with a wavelength of ~ 8 mm at a power level of ~0.5 mw is described in the work of Brannen et al. [32].

The presence of a finite, although comparatively narrow, phase-stability region allows the electron energy in each orbit to be varied smoothly (within known limits), which substantially increases the value of the microtron as an instrument for physical research. This is accomplished as follows. Let us assume that the microtron operates

*In a microtron which accelerates electrons to higher energies, the width of the spectrum is not increased, so that the magnitude of $\Delta W/W$ will be even smaller.

at certain values of H and V_a which correspond to a definite value of φ_s. If, by varying the power supplied to the resonant cavity, the values of V_a and H are changed simultaneously by the same factor, then, according to (21), (18) and (9), the microtron will operate with a new value of c_2, but with the previous value of φ_s. If the change in H is not proportional to that of V_a, new values of both c_2 and φ_s will be obtained. While φ_s remains within the stability region, according to Condition (35), the beam current will be different from zero.

A change in c_2 means, in accordance with (22), that it is also necessary to change c_1. The way in which this is accomplished depends upon the type of injection used in the microtron. In autoelectronic injection the change in c_1 occurs automatically, by shifting the range of suitable electron-emission phases. This, in turn, affects the beam current (see Section 2a). Therefore, it should be expected that when this type of injection is used, there will be several optimum values of V_a and H for each given microtron; at which values the beam current will be maximum. This has also been observed experimentally [6] (Fig. 19).

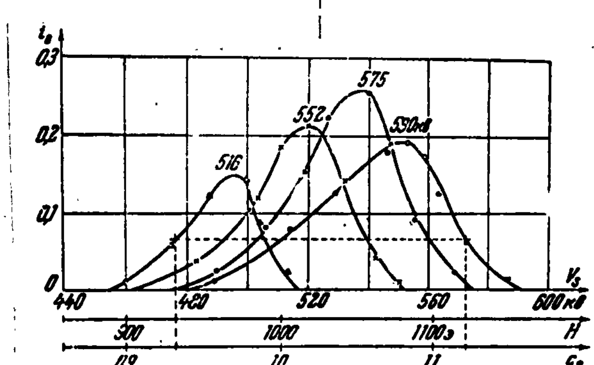

Fig. 19. Beam current versus H at various values of V_a when m = 3, b = 1. The ratio of the 8th-orbit current to the 1st-orbit current under the same acceleration conditions is plotted along the ordinate axis. The dotted horizontal line is drawn at a level of 1/4 the maximum ordinate of the curve with V_a = 575 kv.

Thus, by varying H, we vary the value of c_2 and, therefore, the electron energy in each orbit in accordance with (25); the diameter of each orbit, with the exception of the first, will remain the same, while the beam current will be changed, as shown in Fig. 19. If the beam current under all variations of conditions must not drop below, for example, one fourth of the maximum current, then, when V_a varies from 516 to 590 kv (Fig. 19), the allowable values of c_2 are from 0.95 to 1.12; therefore, the electron energy in the 8th orbit may be varied smoothly from 3.86 to 4.64 Mev. If electrons with energies lower than 3.86 Mev are required, electrons from the 7th orbit should be used (W_7 = 3.36 to 4.06 Mev), etc. Thus electrons with any energy, smoothly variable from 1.9 Mev ($=W_{4,\,min}$) to 4.64 Mev, may be obtained from a given microtron. Electrons with $W < 1.9$ Mev cannot have any energy, since W_3 = 1.43 to 1.78 Mev. Therefore, for example, it is impossible to obtain an energy of 1.85 Mev on either the third or fourth orbit*. For the resonant cavity of this microtron, 1 _0.094 and (sin 1 ≈0.094 and (sin 1 π)/1π ≈0.986 (see Fig. 2). Using the data in Fig. 19 and Formula (9), it can be seen that the optimum values of φ_s, obtained experimentally, are: about 13° when V_a = 516 kv, about 19° when V_a = 575 kv, etc**.

*As is apparent from Fig. 19, when V_a is below 516 kv, that value of V_a will be reached at which a non-zero beam current is already unobtainable no matter what the value of H. However, when V_a is decreased further (and H is decreased correspondingly), the beam will reappear and the microtron will operate with $m = 4$. In this case $c_1 = 3c_2 - 1$, and the maximum value of c_2 will be 0.5, since the limit $c_1 \leq c_2$ holds when autoelectronic injection is used. Under these conditions, a set of curves of the type shown in Fig. 19 may again be obtained. However, the current in the last (in this case the 7th) orbit will be considerably lower in absolute value, since the autoelectronic-emission current drops sharply owing to a decrease in E_a. Operation is also possible with $m = 5$, $c_{2,max} = 1/3$, etc.

**The corrections mentioned at the end of Section 1 were not taken into account in these calculations.

Since the phase-stability range is rather narrow in the microtron, rigid requirements arise for the stability of the values of V_a and H. For example, if the microtron operates at $\varphi_s = 13°$ ($\cos \varphi_s = 0.974$), lowering the value of V_a by 2.6% will shift the equilibrium phase to zero and the beam current will drop to zero. The allowable limits of instability of H depend upon the required beam-current stability and may be determined by experimental curves of the type shown in Fig. 19.

4. Electron focusing

In the previous sections it was assumed that a uniform magnetic field was acting in the microtron. This field does not provide axial focusing of the electrons to be accelerated, and therefore multiple traversing of the resonant cavity would seem to be possible only for those electrons having a sufficiently small axial (z-) component of the initial velocity. In reality, however, there is a slight axial focusing in a microtron. It is created as a result of two factors: 1) the resonant cavity is placed near the edge of the pole, and the center of the accelerating slit is located at a point where $H(r) \neq$ const; the relative drop δH in the strength of the magnetic field in comparison with H in the central region of the interpolar gap is 1 to 2% here; and 2) the HF electrical field of the resonant cavity acts as a weak focusing lens on the electrons traversing it. Previously, it was assumed that the second effect could not exist in practice, since the velocity of the electrons is very close to the speed of light[5]. However, it was shown later [33] that this conclusion was invalid. Resonator focusing causes the electrons to oscillate slowly near the orbit plane; the amplitude of these oscillations increases slowly. A resume of the information on methods and results of the theoretical calculation of the joint action of these two factors is given in Aitken's work [22]. The problem of methods of improving focusing takes on special importance in the case when the microtron is designed for high-energy acceleration, since an electron in this accelerator must traverse the resonant cavity several tens of times. In a 29-Mev microtron [22] the first focusing factor was intensified by special shimming of the magnetic field in the region where the resonant cavity is located, since calculation showed that, without this measure, a very small inclination of the axis of the resonant cavity toward the orbit plane, which is unavoidable in practice, will lead to the complete disappearance of the beam in long orbits.

It has been suggested [2] that magnetic focusing be established in the microtron by using a non-uniform magnetic field, where $H(y) =$ const, and $H(x)$ is a slowly decreasing function; $H(x) = H(-x)$; and the y-axis is directed along the common diameter of all orbits. No detailed calculations have been published.

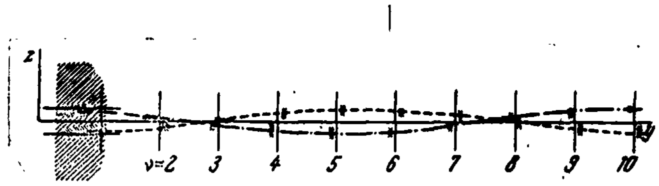

Fig. 20. Results of an experimental study of the axial oscillations of electrons. The shaded areas indicate the location and dimensions of a luminous spot of light on a screen when the latter moves along the y-axis. The left-hand spot in each orbit is connected with electrons from the external emission zone, the right-hand spot, with electrons from the internal emission zone. The y-axis coincides with the common diameter of the orbits and the z-axis is perpendicular to the orbit plane. The vertical lines indicate the theoretical position of the points of intersection of the corresponding orbits with the y-axis.

The following results were obtained in the few experimental studies of electron focusing in a microtron. By using a photographic plate mounted at various azimuths of the first orbit of a 2-Mev microtron (m = 4), it was established that only 1/10 of the electrons which left the resonant cavity on the first orbit traverse the resonant cavity after a single revolution [12]. In a 4.5-Mev microtron [6], using the method of artificial centers of autoelectronic emission (see Section 2a) and a probe with a luminophor screen, the parameters of the axial electron-oscillations were measured separately for electrons emitted from the external and internal emission zones. The results of these measurements are shown in Fig. 20. In the course of ten revolutions, the electrons had time to make only about one complete oscillation near the plane z = 0. Note that the amplitude of the oscillations increases.

Some idea of beam focusing in a microtron can be gotten by examining the experimental data on the distribution of the beam current with respect to the orbits. If the electron losses during acceleration are negligible (starting from the second orbit; for example, in Fig. 18), this not only indicates that losses due to electrons leaving the phase-stability region are small, but also that focusing is satisfactory. Let us note that in some cases [13, 34] electron losses were considerably greater than those shown in Fig. 18. In a 29-Mev microtron [22], the beam current maintained approximately the same level from the 5th to the 32nd orbit, but then it gradually decreased to 1/3 of this level at $\nu = 56$. It is assumed that the main cause of these losses is a slight non-uniformity of the magnetic field. Part of the losses is explained by the fact that the acceleration time of an electron to the 56th orbit is not small in comparison with pulse duration of the resonant-cavity supply ($\sim 0.5\ \mu$ sec and $3\ \mu$ sec respectively). After switching off the resonant cavity, the value of V_a drops rapidly and the further resonance acceleration of electrons which were able to reach this moment, for example, the 30th or 40th orbit, becomes impossible [35]*.

5. Basic information of microtron design

a) The electromagnet. The distinguishing feature of microtron electromagnets is that the strength of the magnetic field in the interpolar gap is low in comparison with the allowable induction in iron (1 to 2 kilo-oersted and 10 to 15 kgs respectively). This means that the cross section of the yoke must be much smaller than that of the pole. For this reason the three-leg yoke, which is characteristic of cyclotron magnets, is the exception in microtrons [37]. The most widely used core shape for microtron electromagnets is shown in Fig. 21. In order to increase the ratio of the diameter of the region of uniform magnetic field to the pole diameter, annular shims may be used. The power dissipation in the windings of the electromagnet usually does not exceed 500 w. Therefore, forced cooling of the windings by air or water is seldom used. The direct current feeding the electromagnet windings is regulated by some electrical circuit; sufficient accuracy of current regulation is ~ 0.1%.

Very high requirements arose for the magnetic system when designing the 29-Mev microtron (with 56 orbits). In this case special measures had to be taken to reduce to a minimum the precession of the orbits near their common diameter, otherwise the electrons could not traverse the resonant cavity the required number of times. For this it is necessary to either create a very uniform magnetic field in the

*These electrons will bombard the resonant cavity, giving rise to hard decelerating radiation. This undesirable effect may be eliminated by installing a device in the chamber in the region of the first orbits for dropping electrons on one of the covers of the chamber. In particular, two electrodes could be used, placed above and below the orbit plane, and which voltage pulses would hit shortly before the instant of switching off the resonant cavity [36].

working region of the chamber, or at least to ensure the best possible symmetry of the field distribution relative to the line of the common diameter of the orbits [38].

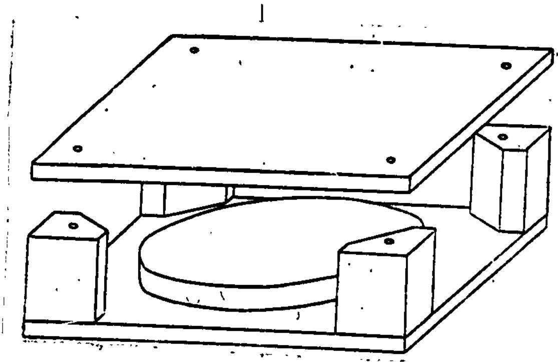

Fig. 21. Structure of magnetic circuit of microtron electromagnet. The upper cylindrical pole, similar to the lower one, is not visible.

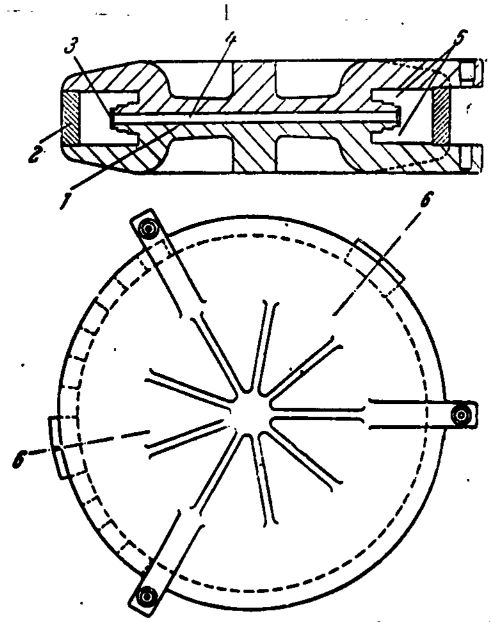

Fig. 22. Magnetic-circuit structure of the 29-Mev microtron. 1--pole; 2--iron inserts, ~40 cm high; 3--aluminum ring, forming a vacuum chamber having an inner diameter of 203.2 cm; 4--interpolar gap, 127 mm high; 5--place for electromagnet windings; 6--outlet axes for vacuum pumps.

An ironclad structure was chosen for the magnet (Fig. 22). The mechanical processing of the pole surfaces was done very carefully. The magnet was provided with a system of compensating windings, attached to the pole surfaces facing each other. Each of these windings has an independent power supply.

A summary of the basic parameters of microtron magnets will be given below.

b) <u>The high-frequency system</u>. Existing microtrons differ very little from one another with respect to the arrangement of the system for supplying HF power to the resonant cavity. The high-frequency oscillator, as a rule, is a magnetron, and only in one case [39] was a triode oscillator with a klystron amplifier used. Fig. 23 shows the typical layout of the HF system of a microtron. Magnetrons with a pulse power of not more than 1 Mw must be used when operating in the 10-centimeter band. A magnetron with a power of 2 Mw is used only in the 29-Mev microtron.

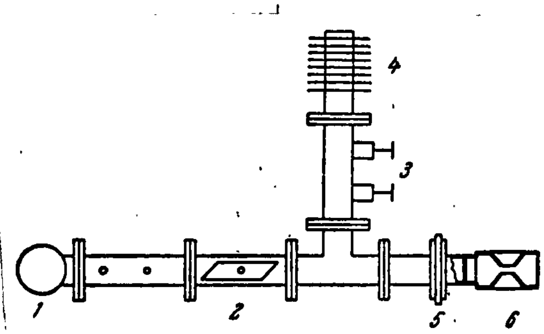

Fig. 23. Arrangement of the HF system of the microtron. 1--magnetron; 2--phase changer, 3--regulator of fraction of power extracted by the regulating load 4; 5--vacuum baffle; 6--resonant cavity.

As an illustration of the balance of power consumption, we shall introduce data for the apparatus which describes the rather high efficiency of the resonant cavity [7]: of the 600 kw of power supplied to the resonant cavity, 400 kw is expended in losses in the walls of the cavity, 100 kw is consumed in the acceleration of all electrons within the resonant cavity, and 100 kw is expended in the further acceleration of resonance electrons (beam current of 15 ma, electron energy of ~7 Mev).

As distinguished from all other cyclic accelerators with phase stability, the microtron is, in principle, an accelerator of continuous action: the process of electron capture under conditions of acceleration is repeated in full in each cycle of the HF field. However, the high power required for exciting the resonant cavity compels operation under pulse conditions with a high duty factor (usually about 1000), in order that the average (with respect to time) power supplied to the resonant cavity does not exceed the allowable limits. It is possible that later the duty factor will be substantially lowered and the beam current increased correspondingly, using magnetrons with high average power and cavities with low losses and intensive cooling.

As a rule, untunable magnetrons are used in microtrons, therefore, the resonant cavity must be equipped with a device for remote trimming of the natural frequency. This is usually accomplished by using a mechanical or thermal system, providing controllable deformation of one of the cavity walls.

The regulating load (see Fig. 23) is usually controlled so that it dissipates about one half of the power supplied to the magnetron. In order that the amplitude of the accelerating voltage have very high stability, it is necessary that the magnetron power supply be regulated.

In autoelectronic injection, since the emission current is dependent upon the value of E_a and since the beam current of the electrons being accelerated exerts an influence upon the magnitude of the cavity voltage, there is an automatic mechanism of stabilization of V_a. It is possible that, under known conditions, a similar mechanism acts when thermal-cathode injection is used.

Kaiser has written a long article devoted to problems in designing the resonant cavity for a microtron [40]. It has been shown recently [6] that certain requirements pertaining to this part of the microtron should be revised. In particular, when designing the resonant cavity it is unadvantageous to aim at maximizing its shunt resistance, since in this cavity the value of V_a will be too strongly dependent upon the beam current.

Some special radio engineering problems connected with the design and building of HF systems for microtrons have been examined [41, 42, 43].

c) The vacuum system. The vacuum chamber of a microtron usually has a cylindrical shape. The chamber is made of non-magnetic metal, and the covers are made of iron. In some cases the covers serve as the magnet poles. During the operation of the microtron, the chamber is evacuated by a pump unit, usually consisting of oil-vapor and rotary pumps. The vacuum requirements in a microtron are very moderate. The electrons quickly acquire high energy, so that even in a poor vacuum, electron losses due to dispersion by residual gas molecules will be practically negligible. Therefore, the upper limit of the chamber pressure is determined by the operating conditions of the resonant cavity or by the supply conditions of its waveguide. In some cases it is sufficient to lower the pressure to $p \leq 10^{-4}$ mm Hg for normal operation of the accelerator. However, at this high pressure the polished surfaces inside the cavity are quickly marred and breakdowns occur more often. Therefore, it is usually desirable to operate at a pressure $p \leq 10^{-5}$ mm Hg.

In autoelectronic injection, according to Kaiser [18], a dependence of the emission current upon the chamber pressure is observed, and optimum pressure is from 10^{-4} to 10^{-5} mm Hg. A higher vacuum may be required when certain types of thermal cathodes are used, due to the possibility of oxygen "poisoning" at high temperatures.

d) Auxiliary equipment for observing electron acceleration. A Faraday cup is used to measure beam current in various orbits. Its holder is lead out from the chamber through a sliding vacuum seal. A luminophor-covered screen, attached to a handle with the same kind of seal, is used for visual observation of the beam. The luminescence of this screen when it is bombarded with electrons is observed through a window; a system of mirrors and television apparatus may be used [6]. An unusual system is used in the Swedish microtron for visual observation of the beam [39]. Fifteen tungsten filaments, with a diameter of 0.1 mm and placed horizontally, one above the other, at intervals of 1.25 mm, are mounted on a long frame, which is set up on the lower cover of the chamber, approximately along its diameter. During operation of the microtron, these filaments glow in those places where the electron orbits pass, and, thus, all orbits may be observed simultaneously and information obtained on the dimensions of the electron-cluster cross section in each orbit.

e) The extraction of electrons from the chamber. The distinguishing feature of the microtron is the change in the energy of the particle being accelerated after each passage through the resonant cavity and, as a result of this, the great distance between adjacent orbits. If the "spacing" γ of the spiral path of an electron is measured along the common diameter of the orbits, then $\gamma_\nu = D_{\nu+1}$, where D_ν is the diameter of the ν-th orbit. From the well known relationship between the magnetic rigidity G of the electron and its total energy E, eG =

$\sqrt{E^2 - E^2}$, using Formulas (21) and (25), it is easily found that

$$D_\nu = \frac{\lambda}{\pi}\sqrt{(m-2+\nu)^2 - \frac{1}{c_2^2}} \qquad (\nu = 2, 3, \ldots). \tag{36}$$

When $\nu \geq 5$ and $c_2 \geq 0.5$, the approximate formula

$$D_\nu \simeq \frac{\lambda}{\pi}(m-2+\nu) \tag{37}$$

gives the result with an error of less than 6%. Thus, at high values of ν

$$\gamma \simeq \frac{\lambda}{\pi}, \tag{38}$$

which, when λ = 10 cm, is ~ 3.18 cm. When the spacing is this large, the problem of extracting a beam of accelerated particles from the magnetic field is not difficult.

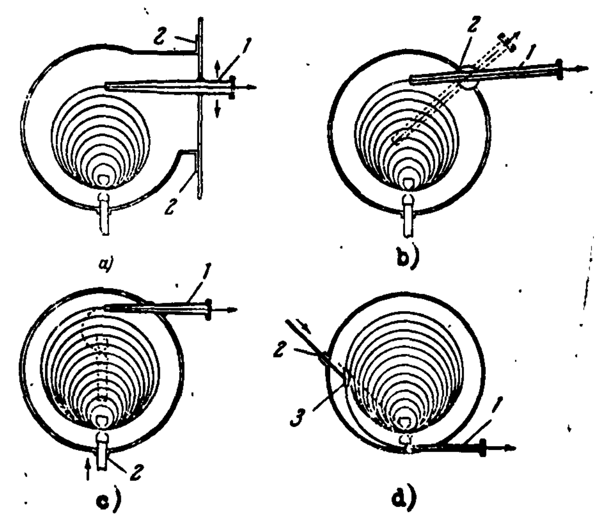

Fig. 24. Various devices for extracting the beam from the vacuum chamber. 1--iron tube; 2--sliding vacuum seal (of varied structure); 3--short iron tube. Versions a), b), c), and d) described in [37], [44], [45], and [46] respectively.

Many types of extraction devices have been developed so far. An "antimagnetic channel" is used in each of these; an iron tube in the hollow of which the strength of the magnetic field is very low, due to the shielding action of the walls of the tube. An electron beam moves almost rectilinearly through this tube and is easily extracted from the chamber. The most universal extraction device satisfies the following requirements: 1) it must be possible to extract electrons from any orbit (starting from the second); 2) the extracted beam must hit the same fixed aperture in the experimental apparatus in which it is used, regardless of which orbit it has been extracted from; and 3) the beam must enter this fixed aperture in the same direction. Fig. 24 shows schematically all suggested versions of the extraction device except the earliest version, which was designed to extract the beam only from the last orbit. All four versions satisfy the first requirement, but only versions c) and d) satisfy the second and third requirements. So far no information has been received on the use of version c) in practice.

A combined system of beam extraction is used in the Swedish microtron [39]: first of all the beam is deflected by an electrostatic deflector with $E = 45$ w/cm, and then enters an "antimagnetic channel."

In microtrons, the current of the extracted beam is usually 50 to 70% of the current circulating in the corresponding orbit.

In conclusion, let us summarize the main parameters of the working microtrons and of one under construction [47] (Table III). Some microtrons were not described in detail in the literature, and only incomplete data can be given concerning them.

f) <u>Various suggested modifications and improvements in microtron design</u>. In 1946, a short article [3] appeared concerning a modification of the microtron suggested by Schwinger. It was suggested that a split magnet be used. It is made up of the two sections formed when a magnet with cylindrical poles is cut along their diameter and the halves are separated by a certain distance. The accelerating system may consist of one or several resonant cavities; in the latter case the resonant cavities must be excited from a single generator and have the proper phase shift relative to one another. The resonant cavities are placed in the space between the sections of the magnet. This makes it possibly to increase considerably the height of the interpolar gap of the magnet, making it only a bit larger than the diameter of the gap in the resonant cavity.

A powerful accelerating system can impart a high energy gain to electrons in each orbit. $c_2 \geq 2$ may be obtained, so that the magnetic system will be very compact.

In this version of the microtron, as in the ordinary microtron, there is only a weak beam focusing during transit through the resonant cavity. However, a more powerful lens may be installed together with the resonant cavity, for example, quadrupole magnets. In addition, the electron beam may be well focused even before entering the magnetic field, since in this version there is sufficient space for setting up a high-quality electron gun; in this case high-energy injection may also be obtained.

In a microtron with a split magnet, the resonance conditions have a form which is somewhat different from that in the usual microtron [18, 50, 12]. Some problems of theory, particularly the problem on the width of the phase-stability region as a function of the distance between the sections of the magnet, have been examined by Turi [50]. Many other problems, for example, concerning the effect of a dispersed magnetic field upon electron motion, have yet to be treated.

So far no information has appeared concerning the construction of a microtron of the type described here.

In 1953, in the Soviet Union [51] and Japan [52], and independently in the United States in 1955 [52], cyclic, strong-focusing accelerators were proposed which have a constant (with respect to time) magnetic field (in English they are called "FFAG accelerators").

Data on the possibilities of applying the principle of these accelerators to the microtron has so far not appeared in the literature, with the exception of the initial discussion [18].

Another new type of accelerator having a constant magnetic field and strong focusing, the so-called accelerator with contiguous orbits, has been proposed and treated in detail theoretically in a number of works by Ye. M. Moroz [53, 54, 55]. The magnetic system of this accelerator consists of several sections of a specially designed shape and has a uniform magnetic field in the interpolar gap of each section.

Strong particle-focusing is accomplished as a result of the action the outer magnetic field at the points of entry of the particles being accelerated into the magnetic sections and at the points of exit from these sections. Thus, a microtron with a magnetic system of this type will have the same virtues as a microtron with a split magnet (described above), but will have magnetic particle-focusing, the lack of which is the main drawback of a microtron with a split magnet. Calculation showed that a sectional magnetic system can be constructed with a very wide range of stability of motion of accelerated electrons.

Unfortunately, there is so far not work in which all these theoretical conclusions have been checked experimentally. It was reported recently [32] that the construction of a 4- to 12-Mev microtron with a four-section magnetic system is nearing completion. Interesting data on the design and operation of this microtron may be found in the article by Brannen and Froelich [62].

6. Conclusion

At the present time it is difficult to say exactly to what energies future microtrons will be able to accelerate electrons. One of the main advantages of a 5- to 10-Mev microtron is its simplicity. It is the only accelerator which can be built in any laboratory having a machine shop. When moving to higher energies, the advantage of simplicity is lost. The 29-Mev microtron, whose parameters are described above, required a very carefully constructed magnet with a complicated system of compensating windings; after prolonged adjustment of the accelerator, the beam current attainable in the last orbit was very low. Apparently, the upper limit of energy of electrons accelerated in a microtron is somewhere between 50 and 100 Mev [7, 56].

Modern powerful magnetrons can operate when the pulse duration of the HF voltage does not exceed a definite value (~ 3 to 8 μsec). This fact imposes a limit on the electron energy attainable in a microtron, since when the required number of orbits is high, the over-all duration of the acceleration process may equal the duration of the operating range of the resonant cavity. It happens, however, that the obtainable (on the basis of these considerations) values of the limiting electron energy are very high [35], so that the maximum attainable electron energy in a microtron is determined, in practice, not by the pulse duration of the magnetron, but by other factors, particularly the difficulty of creating a magnetic field with the required high degree of uniformity (in a microtron without sectional focusing).

In principle, it is possible to create a microtron-type accelerator in which not only electrons, but also ions, may be accelerated up to any energy desired, starting from ~ 1 Gev [57]. A sectional magnetic system of the type suggested by Ye. M. Moroz [54] and an injector in which particles are accelerated to an energy exceeding 0.5 Gev must be used for this. If is suggested that a specially designed linear accelerator be used also, but already this device is not a microtron. The author suggested that this accelerator be called an "oxinotron."

The question on the maximum attainable beam current (pulse) of accelerated electrons is also essential. Its magnitude is determined by the maximum injection current, the degree of electron focusing during acceleration and the effective power of the magnetron. If, when $\lambda \sim 10$ cm, the latter is 800 kw, then, taking the losses in the resonant cavity and its power system into account, a power of ~300 kw may be used for electron acceleration. This means that when the electron energy is 5 Mev, the beam current may reach 60 ma (pulse), and when the energy is 20 Mev, the beam current can reach 15 ma (pulse)*. When the magnetron power is higher, the maximum beam current will be correspondingly higher.

There is, however, another factor which may limit the beam current. I a microtron electrons move in a curvilinear path and, therefore, lose energy by electromagnetic radiation. Radiation energy losses for an individual electron are extremely small in the usual microtron (e.g., when $W = 29$ Mev and $H = 1.07$ kilo-oersted, $\Delta W \simeq 0.07$ kv/rev) and no influence is exerted on electron acceleration. However, in

*Remember that the beam currents reached in a microtron are 20 ma at 6 Mev [39] and 5 ma at 12 Mev [7].

view of the fact that in a microtron the electrons form highly compact clusters, the role of coherent radiation increases greatly [3]. As is known, in this case each electron radiates per unit path length energy proportional to the number of electrons in the cluster. Thus the magnitude of the energy loss is strongly dependent upon the beam current. If the beam current exceeds a determined value, energy losses by radiation will be so high that electrons will fall out of the region of phase stability.

When averaging the value of the beam current with respect to time, it is necessary to remember the effective duty factor of the resonant cavity, i.e., the duty factor calculated taking into account only that part of each pulse during which the amplitude of the accelerating voltage already has a steady-state value and maintains that level. In addition, it is necessary to remember the relationship between the effective pulse duration of the resonant cavity and the duration of the process of accelerating an electron to a given energy [35].

The accelerator with an electrostatic generator (ESA), the betatron, synchrotron and the linear waveguide accelerator (LWA) are also well developed and widely used.

Let us compare the microtron with these four types of accelerators with respect to some of their most essential parameters.

1. The upper limit of electron energy. In this respect, only the ESA is inferior to the microtron, while the other three accelerators make it possible to obtain electron energies tens and hundreds of times greater than those possible in the microtron.

2. The upper limit of beam current. In betatrons and synchrotrons, the pulse beam current (even if the pulse duration is made

very small ~ 2 μ sec) is lower by a factor of tens than that attainable in a microtron. The ESA provides a continuous beam; the beam current is much greater than the average (with respect to time) beam current in a microtron, but lower than the pulse current. The LWA of medium energy (to 100 Mev) can provide up to 0.8 a (pulse).

3. <u>The energy uniformity of accelerated electrons.</u> Regarding this parameter, the ESA has an advantage over the microtron. As was already noted, the energy spread of electrons in a microtron does not exceed $\pm$50 kv due to the narrowness of the phase-stability region. Thus in a microtron when W = 20 Mev, $\delta W = \pm 2.5 \cdot 10^{-3}$. The LWA can approach the microtron with respect to the magnitude of δW only when special measures are taken regarding beam-intensity losses.

4. <u>Constancy of the average energy of accelerated electrons over an extended period of time.</u> Regarding this parameter, the microtron also has an advantage over the other accelerators except the ESA. The constancy of the energy of accelerated electrons is ensured by stabilizing the strength H of the master magnetic field; since a constant magnetic field is used in the microtron, a very high stability factor of H may be obtained.

5. <u>The pulse duration of the electron current striking the target.</u> Here we don't mean macropulses, whose width is determined by the pulse duration of the supply to the magnetron and is usually 1.5 to 2 μ sec, but "micropulses," whose duration is dependent upon the length of the individual cluster of electrons and is in all about $3 \cdot 10^{-11}$ sec when λ = 10 cm (and under certain conditions it is even smaller [31]). The microtron gives the shortest micropulses of all working pulse accelerators, which for certain applications is a decided advantage.

FIRST LINE OF TEXT

Table 3

Parameters	Location of Microtron												
	Moscow [7]	Tomsk [47]	London (Canada) [5, 44]	London (Great Britain) [13]	Washington (USA) [34]		Washington (USA) [37]	Braunschweig (West Germany) [6]	Naples (Italy) [29]	Budapest (Hungary) [48,12]	London (GB) [22,38]	Mainz (West Germany) [19]	Stockholm (Sweden) [17,32]
Maximum kinetic energy of electrons, Mev	6,8 (11,6)	5,1	5	4,5	0,8	3,3	3,06	4,6	2,5	2	29	10	5,9
Electromagnet													
Pole diameter, cm.	70	55	41	43,2			~20	56	60	46	203,2	50	47
Height of interpolar gap (or internal height of chamber), cm.	11	12,5		9,5				10		11,7	12,7		
Nominal strength of magnetic field, kilo-oersted.	1,18 (1,95)	1,07	~1	~1	to 1,68	to 1,68	to 1,68	1	0,52	0,5	1,07		1,23
Power supply, kw.				0,45						<0,3			
Weight, t.											20		0,7
High-frequency system													
Wavelength, cm.	10	10	10,7	10	3,2	3,2	3,2	10,7	10,23	10,61	10		9,95
Equilibrium voltage, kv.	562 (932)	511	511	490	255	255	255	~500	255	250	511		585
Length of accelerating slit, mm	16,3 (23,2)		10	7,8				10	7,95	7	7,8		10
Diameter of gap in resonant cavity, mm.		10	9,5					11	7,2		8,5		9
Q-factor of resonant cavity (without load)			10^4	9500	4100			7000 (4500)	8000	5300	9500		6000
Shunt resistance of resonant cavity, Mohm.			2		1,3			0,52	1		1—2		0,70
Power input to resonant cavity (pulse), kw.	600 (?)		300	250			<50 (without beam)	300	200	125	~10^3		
Pulse duration of resonant-cavity supply, μsec.			2		0,25		0,12÷÷1	1÷3	1,6	2,2	3		2,7
Pulse repetition rate, p/sec.		345	435	200	to 10^3		200÷÷2000	13÷÷1000	200	300	100		12,5
Beam characteristics													
Number of orbits.	12	9		8		14	12	8	10	8	56		10
Diameter of last orbit, cm.	41,4	34,9		30		15,22	14,1	~34	38		184		31,8
Beam current (pulse) in last orbit, ma.	15 (5)		1	0,5		0,04	0,1	до 0,1	1	0,01	0,05		20
Maximum beam-extraction efficiency, %	80			70				70		60	30		

3
2
1
0

STOP HERE

Regarding only the first four parameters examined above, it may be said that only the LWA could almost in all cases replace the microtron. In a more detailed comparison of the various electron accelerators, made taking the required type of operation of the given microtron into account, other parameters may prove to be essential, for example, the cost of the apparatus, its mobility, over-all and specific volume (i.e., the volume required per 1 kw beam power, the power efficiency of the accelerator, the possibility of varying the energy of accelerated electrons continuously and within wide limits, the characteristics of the extracted beam (the yield factor), the beam diameter, and the angular divergence.

The inherent parameters of the microtron make it a very effective injector for a large synchrotron [18, 16, 17], and a convenient accelerator for generating submillimeter waves [31, 32] and for nuclear physics research using the transit-time method [18].

Note that the microtron is used to study electron scattering (it is suggested that the radiative correction be determined in the elastic scattering of electrons [58]) and for studying the action of electrons with an energy of 2 Mev upon the rotation angle of the plane of polarization in a fluid [59].

The short duration of electron micropulses, inherent in microtrons, makes it difficult to set up experiments in which particle or quanta counters are used which have a comparatively long dead time [6]. However, this drawback may be overcome by using reasonably designed apparatus.

So far the articles published by laboratory workers who have built microtrons have been devoted, for the most part, to problems of studying the accelerator itself. No doubt, in the future, more publications will appear concerning physical studies made using an electron beam from a microtron.

The modern 10- to 20-Mev microtron, designed on the basis of progress made in this area, will be a compact accelerator with sufficiently high beam current. This microtron will probably supercede the betatron, which is at the present time used in industrial defectoscopy and in medicine.

REFERENCES

1. V. I. Veksler. DAN SSSR, 43, 346, 1944; J. Phys. USSR, 9, 153, 1945.

2. J. Itoh and D. Kobayashi. Kagaku 17, 34, 1947; Sci. papers from the Osaka Univers., No. 12, 1, 1949.

3. L. I. Schiff. Rev. Sci. Instr. 17, 6, 1946.

4. W. J. Henderson and H. LeCaine and R. Montalbetti. Nature 162, 699, 1948.

5. P. A. Redhead, H. LeCaine and W. J. Henderson, Canad, J. Res. A28, 73, 1950.

6. H. Reich. Z. Angew. Phys. 12, 481, 1960.

7. S. P. Kapitsa, V. P. Bykov and V. N. Melekhin. ZhETF, 39, 997, 1960.

8. C. Schmelzer and Z. Naturforsch. 12, 808, 1952.

9. H. F. Kaiser. Rev. Sci. Instrum. 25, 1025, 1954.

10. Ye. M. Moroz. DAN SSSR, 106, 986, 1956.

11. H. L. Knudsen. Trans of the Danish Acad. of Techn. Sci., No. 3, 3, 1949.

12. E. Kisdi-Koszo and L. Turi. Nucl. Instrum. and Methods, 9, 137, 1960.

13. C. Henderson, F. F. Heymann and R. E. Jennings. Proc. Phys. Soc., B66, 654, 1953.

14. A. Paulin. Nucl. Instrum. and Methods 5, 107, 1959.

15. A. Paulin. ibid, 9, 113, 1960.

16. M. Sedlacek. Ark. fys. 11, 129, 1957.

17. O. Wernholm. Ark. fys., 16, 525, 1960.

18. H. Kaiser. IRE Trans. NS--3, No. 2, 17, 1956 (translated in the collection "Millimeter and Sub-millimeter Waves," Moscow, IL, 1959).

19. H. Reich and J. Trier. Phys. Verhandl. 8, 163, 1957.

20. B. Z. Kanter, Izv. vuzov (Fizika), No. 3, 138, 1960.

21. D. K. Aitken. Proc. Phys. Soc. A70, 550, 1957.

22. D. K. Aitken, F. F. Heymann, R. E. Jennings and P.I.P. Kalmus. Proc. Phys. Soc., 77, 769, 1961.

23. A. A. Kolomenskiy. Trudy FIAN, 13, 3, 1960 (see reference 16 in this work).

24. C. Henderson, F. F. Heymann and R. E. Jennings. Proc. Phys. Soc. B66, 41, 1953.

25. A. A. Kolomenskiy. ZhTF, 30, 1347, 1960.

26. M. Rabinovich. J. Phys. USSR, 10, 530, 1946.

27. E. Kisdi-Koszo. Acta Physica Acad. Sci. Hungarica, 4, 377, 1955.

28. E. Kisdi-Koszo. Repts. of the Central Inst. for Physics of the Hungarian Acad. of Sci., 4, 499, 1954.

29. A. Carrelli and F. Porreca. Nuovo cimento 6, 729, 1957.

30. V. L. Ginzburg. Izv. AN SSSR, ser. fiz., 11, 165, 1947.

31. I. Kaufman and P. D. Coleman. J. Appl. Phys. 27, 1250, 1956.

32. E. Brannen, H. Froelich and T. W. W. Stewart. J. Appl. Phys., 27, 1250, 1956.

33. J. S. Bell. Proc. Phys. Soc. B66, 802, 1953.

34. H. F. Kaiser. J. Frankl. Inst. 257, 89, 1954.

35. F. Porreca. Nuovo Cimento 11, 283, 1959.

36. R. E. Jennings. Electrical Rev. 161, 309, 1957.

37. H. F. Kaiser and W. T. Mayes. Rev. Sci. Instrum. 26, 565, 1955.

38. G. R. Davies, R. E. Jennings, F. Porreca, and R. E. Rand, Nuovo Cimento 17, suppl. No. 2, 202, 1960.

39. O. Wernholm. Private communication.

40. H. F. Kaiser. J. Frankl. Inst. 259, 25, 1955.

41. J. Lehocz and J. Palinkas. Repts. of the Central Inst. for Physics of the Hungarian Acad. of Sci. 5, 43, 1957 (see also p. 483).

42. H. Reich. Nucl. Instrum. 3, 97, 1958.

43. M. Innas Ali. Pakistan J. Sci. and Industr. Res. 1, 26, 1958.

44. E. Brannen and H.I.S. Ferguson. Rev. Sci. Inst. 27, 833, 1956.

45. Hsieh Chia-lin. Sci.Record, New Ser. 1, 227, 1957.

46. H. Reich and Z. Naturforsch. 13a, 1003, 1958.

47. A. A. Vorob'ev. In the collection "Problems on the History of Natural Science and Engineering," No. 8, Moscow, Izd. AN SSSR, 33, 1959.

48. E. Kisdi-Koszo and L. Turi. Acta Physica Acad. Sci. Hungar. 12, 273, 1960.

49. G. Lehr and B. Godesberg. Atomwirtschaft 4, 277, 1959.

50. L. Turi. Repts. of the Central Inst. for Physics of the Hungar. Acad. of Sci. 7, 111, 1959.

51. A. A. Kolomenskiy, V. A. Petukhov and M. S. Rabinovich. In the collection "Some Problems on the Theory of Cyclic Accelerators," Izd. AN SSSR, 7, Moscow, 1955.

52. K. R. Simon, D. V. Kerst, L. V. Jones, L. G. Laslet and K. M. Tervilinger. UFN, 61, 613, 1957.

53. Ye. M. Moroz. DAN SSSR, 108, 436, 1956.

54. Ye. M. Moroz. DAN SSSR, 115, 78, 1957.

55. Ye. M. Moroz. Atomnaya energiya, 4, 238, 1958.

56. R. E. Jennings. Contemp. Phys. 2, 277, 1961.

57. A. Roberts, Ann. of Phys. 4, 115, 1958.

58. M. R. Bhiday, R. E. Jennings and P.I.P. Kalmus. Proc. Phys. Soc. 72, 973, 1958.

59. A. Carrelli and F. Porreca. Nuovo Cimento 19, 844, 1961.

60. V. P. Bykov. ZhETF, 40, 1658, 1961.

61. A. Paulin. Nucl. Instrum. and Methods 12, 155, 1961.

62. E. Brannen and H. Froelich. J. Appl. Phys. 32, 1179, 1961.

63. S. P. Kapitsa, V. P. Bykov and V. N. Melekhin. ZhETF, 41, 368, 1961.

FIRST LINE OF TITLE

STOP HERE STOP HERE

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE	Nr. Copies	MAJOR AIR COMMANDS	Nr. Copies
		AFSC	
		SCFTR	1
		ARO	1
HEADQUARTERS USAF		ASTIA	10
		TD-Bla	3
AFCIN-3D2	1	RADC (RAY)	1
		SSD (SSF)	1
		ASD (DCF)	1
		ESD (ESY)	1
OTHER AGENCIES		AFSWC (SWY)	1
		AFMTC (MTW)	1
CIA	1	APGC (PGF)	1
NSA	2		
AID	2		
OTS	2		
AEC	2		
PWS	1		
PGE	1		
RAND	1		