MODERN DEVELOPMENTS OF THE MICROTRON

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A review of the principal results obtained in the study and development of the high-current microtron is presented. At present the development of the microtron has left the primary stage when the accelerator itself was the major object of investigations. Now, after a number of machines for different purposes have been successfully built, time has come to examine the possibilities that this type of accelerator opens for research and the trends that will develop in the future years. Before passing to the description of modern achievements in this field we will remind the basic principles of the microtron and surfey the innovations that have led to new developments of this accelerator.

The idea of the electron cyclotron, later called the microtron was proposed in 1944 by Veksler in his very first paper on the principle of phase stability (1). In the microtron electrons are accelerated by an alternating electric field of a cons tant frequency in a uniform and constant magnetic field. In the vacuum chamber the electrons move along circles having a common tangent point. At this point the accelerating resonator is placed. On each passage through the accelerating cavity the electrons obtain a certain amount of energy and pass to the next circle, or orbit. Synchronism of the electrons and of the accelerating field is maintained by making each next turn longer than the previous one by just one period[1] of the high-frequency field T. The time of revolution in a magnetic field of a relativistic particle is proportional to its total energy E, $t = 2\pi E/eHc$ and so the condition of synchronism for a microtron may be expressed by the correspondence between the energy gain ΔE and the increase in the time of revolution $\Delta t = 2\pi \Delta E/eHc = T$. It is convenient to transform this expression to a ratio introducing the parameter Ω that is basic for the description of a microtron. $\Omega = \Delta E/E_0 = H/H_0$ where $E_0 = m_0c^2$ is the rest energy of the electron, $H_0 = 2\pi E_0/e\lambda$ is the cyclotron magnetic field for the operating wave length λ.

Ω is the principal parameter of the accelerator and its main properties, energy, and current limit are dependent on this quantity. In a microtron Ω is of the order of unity, so in each passage through the resonator the energy gain of the particle is approximately equal to its rest energy. This is the basic difference of the microtron from all other phase-stable cyclic accelerators such as synchrotrons and synchro-cyclotrons in which the energy gain per revolution is much less than the energy of the particle and can usually be considered to be a small quantity in the theoretical treatment. The main consequence of this, from an experimental point of view, is that the electric field in the cavity is comparable to the guiding magnetic field. For electrons $E_0 = 511$ keV the realisation of such an energy gain per turn is the main difficulty in constructing a microtron. This leads to high fields and high powers in the cavity that can be obtained only through the use of modern high-power microwave devices. On the other hand, the theory of the microtron is dependent on numerical methods for the exact solution of the equation of motion because one cannot treat the electric field and the energy gain per turn as a small quantity in calculations. It is obvious that in the present form of the microtron it is not possible to accelerate heavy particles because their rest energy is to large, although an attempt to modify the microtron for accelerating protons has been examined in some detail (2). In the proposed proton microtron the necessary tolerances of the magnetic field and very high energy gains per turn led to difficulties that are not easily surmountable using modern techniques. This work (2) and others (3) have led to an idea of modifying the magnetic field of the microtron by introducing edge focusing and field free areas. The edge focusing magnet has been successfully

[1] Other modes in which the difference may be 2 or 3 T are possible, but they have a smaller range of phase stability and do not find general use.

used on a small electron microtron which we will discuss later (4).

In a microtron after N passages through the resonator the energy of the electron that is moving at an equilibrium phase will be

$$E_N = N \Omega E_o + E_i$$

where E_i is the injection energy. For initial synchronism the injection energy must be chosen so as to make the first orbit an integer number of accelerating periods long.

We will not examine in detail the phase motion in the microtron but will only note that the stable phases occupy a narrow region between 0 and 32° ($\varepsilon \sim \cos \varphi$). There is no appreciable radiation damping of the phase motion in the microtron. The angular phase volume is conserved during the process of acceleration leading to a slight spread of the accelerated beam energy δE independent of the number of orbits.

The small range of acceptable phases leads to difficulties with the injection of particles into the microtron. Earlier in the microtron toroidal cavities were used. The injection of electrons was by field emission from the edges of the accelerating gap and in this case the injection energy $E_i = o$. The accelerator operated at $\Omega = 1$ (or $\Omega = 1/2$) and the energy of the beam was a multiple of the rest energy $E_N = NE_o$. With this type of injection the capture of electrons per accelerating phases was difficult to control, the focusing of the beam was poor, and so the current and efficiency of the macchine were very low. Mainly because of this the microtron was considered not to be an efficient accelerator.

The main developments that led to the modern high-current microtron were new methods for injecting and focusing the electrons. The method developed at the Institute for Physical Problems is based on the use of a thermo-emitting cathode placed directly at the surface of the resonator. As resonators rectangular or cylindrical cavities with E_{110} or E_{010} field respectively were used that have some resemblance to a single cavity of a linear accelerator (5, 6).

The emitter of electrons is places on the inside surface of the cavity and the emission of the electrons is due to the direct action of the high-frequency electric field. The current is governed by the temperature of the cathode.

To stable accelerating phases electrons may be captured in different ways. In the first mode of capture the cathode is placed at about half of the radius of the resonator, and the first half turn (orbit) takes place inside the resonator. At fixed dimensions of the cavity and the position of the emitter injection can take place for different Ω usually from 0.7 to 1.6 (6). By changing the magnetic field and the energy gain per turn one can continuously change the exit energy of the electron beam at least twice without changing the number or position of the electron orbits. This is a new property of these modes of acceleration that are practically important because they lead to full control of the beam energy.

In the second mode of acceleration the emitter is placed not far from the center of the cavity and the electrons have to pass through an auxiliar hole in the resonator. In this case the cavity may be designed for Ω from 1.7 to 3 but with less latitude for changing the energy at a given geometry. The energy gain is from 900 keV to 15 MeV per passage through the cavity, and these modes are most suitable for high-energy operation and have been extensively used on our large machines (7).

As an emitter the most successful substance employed at present is lanthanum-boride, LaB_6 efficiently emits at 1600 ÷ 1700°C, and under the high fields in the cavity it can stably operate at a very high current density, up to 100 A/cm^2 or even more. These current densities are produced through the enhancement of emission by the Shottky-effect. The number of electrons captures is determined by the detailed dimensions of the cavity and can be further raised by biassing the emitter. The negative bias is introduced by grounding the emitter through a resistor (8). Additional initial focusing may be obtained by slightly depressing the emitter below the surface of the cavity. The form and the position of the emitter, the exact size of the cavity, the efficiency of electron capture to accelerating phases, and all the principal features of the dynamics of the electrons in such cavities can be directly calculated by numerically integrating the equations of motion of an electron in the electric and magnetic field of the microtron.

Electrons have been successfully injected into a toroidal resonator by an external electron gun of special coaxial design that was developed for the microtron at Lund (Sweden). This pulsed electron gun operated at 80 kV and also uses a lanthanum-boride emitter (9).

Vacuum requirement for the microtron do not seem excessive and most machines use standard oil diffusion pumps. The electric strength of the resonator to a certain extent depends on the vacuum and I F P machines require a pressure $2 \cdot 10^{-6}$ torr. Under such conditions vacuum annealed OFHC copper cavities successfully operate at fields 600-1000 kV/cm.

In the microtron the distance between the orbits is practically constant and equal to λ/π (30 mm at $\lambda = 10$ cm). The extraction of the beam from the accelerator is a simple matter. Electrons are usually guided through an iron tube that screens the magnetic field at the last orbit. By suitably shimming the magnetic field the perturbations due to the presence of the tube may be compensated for and the current losses at extraction are negligible (10). An alternative way for compensating the disturbances of the magnetic field by currents distributed near the tube has been developed (8).

Because of the small angle of phase stability the electrons are bunched into compact bunches 1/15 - 1/20 λ long that follow each other at a distance of one wave length λ (11). The energy spread δ E is proportional to δ E = 30 Ω keV and does not depend on the number of orbits.

The magnetic field that is necessary for the operation of the microtron must be uniform and constant. The field in the vacuum chamber is 1000÷2000 Oe and is usually produced by an electromagnet, although some consideration has been given for constructing a permanent magnet (12). The homogeneity of the magnetic field is determined by the shape of the pole pieces. The tolerances on the magnetic field are determined by the number of orbits N, and the admissible inhomogeneities vary as $\delta H/H \sim 1/N^2$ (13). An inhomogeneity of the magnetic field that is particularly dangerous for the operation of a microtron, especially with a large number of orbits is a slope of the magnetic field across the common diameter of the orbits that leads to a radial drift of the electrons.

The focusing in the microtron with a uniform magnetic field is due to the action of the resonator. Contrary to the case of the linear accelerator, the electromagnetic field in the cavity exerts a definite focusing action on the electrons maintaining their stability of motion because of the positive phases at which the microtron operates. The degree of focusing exerted by cavity is determined by the shape of the transit holes and the thickness of the resonator (14, 15). Theory and experiments show that by suitably shaping the resonator holes one can ensure sufficient axial stability for accelerating electrons up to at least 30 orbits (7). The focusing by the cavity is of the alternating gradient type and a matrix method for studying the beam dynamics has been developed. In a certain sense the strength of focusing can be described by that of a cyclotron field with n ~ 1/16. It is important to note that the axial and phase motion is periodic in the number of orbits. In other words, the motion is periodic in the frame of the electron, but is non-periodic in the laboratory frame of reference. In the case of optimum stability electrons oscillate with a period of 4 orbits. As in the case of phase motion that has a period of 5 to 6 orbits depending on the equilibrium phase, there is no vertical damping.

The radial focusing in the microtron is more complicated. Some of the focusing comes from the constant magnetic field (360° focusing), the rest is due to the action of the cavity. The motion of the orbits is aperiodic and the electrons are gradually drawn to the axis of the resonator if there are no disturbing perturbations.

The high-frequency system of a microtron usually consists of a high-power microwave generator coupled to the resonator. In the earlier microtrons matching was achieved using a parallel water load that leads to considerable power losses. Modern machines usually employ ferrite isolators or circulators. Most machines use pulsed magnetrons that seem to be most suitable although one the Lund microtron high-power klystrons have been successfully used. The power that is necessary to excite the resonator of the microtron is proportional to Ω^2 and a wavelength of 10 cm and Ω = 1 is usually about 250 kW. The efficiency of modern microtrons determined as the ratio of the beam power to the power that enters the resonator is usually from 30 to 35%.

Practically all the pulsed microtrons operate in the S-band (10 cm). This wavelength seems to be most suirable for the operation of microtrons. Passing to a higher frequency would require very high fields in the resonator, especially using high Ω modes of acceleration and would lead to excessively high current densities at the emitter. All microtrons operate as pulsed machines, with a duty ratio of 1000 and pulse lengths of a few microseconds.

In principle the microtron is a C W accelerator. It is interesting to examine the possibilities of a C W microtron for modern developments in C W microwave generators have reached the power level at which such a C W microtron is feasible (16, 17). The operating frequency for a C W microtron is lower than the S-band and lies between 1500 to 2000 mc. The principal factor determining the frequency is the high heat flux in a C W operated microwave cavity of the microtron; that is the most critical par of the machine.

At present it seems reasonable to build a C W microtron with a magnet, 3 or 4 m in diameter with a beam power of 10 to 30 kW for energies up to 30, may be 40 MeV. High-power magnetrons or klystrons are at present available for power levels of approximately 150 kW. The approximate size of a C W microtron will be comparable to the size of a standard Lawrence type cyclotron.

The maximum energy that can be obtained in a microtron depends on the number of orbits and the parameter Ω. The maximum number of orbits is determined by the tolerances on the magnetic field and the sixe of the magnet. Without introducing any special means for compensating the inhomogeneities of the magnetic field, high current microtrons have been successfully operated at 30 orbits and $\Omega = 2$. By introducing special coils a 2 m magnet for a 56 orbits microtron has been built in London (18). The operation of this machine was not really successful because of the lack of focusing from the resonator (19) and to the knowledge of the author work with this machine has stopped.

It is reasonable to suppose that the maximum number of orbits for the microtron is approximately 50, may be 100. Taking into account the possibilities of using high Ω accelerating modes the reasonable limit of the energy of a microtron can be estimated as 100 MeV.

The current of the beam is naturally determined by the high frequency power. At present microtrons have operated up to currents of 100mA. Theoretical estimates of the currents at which interaction with the cavity and the coherent radiation of the bunches lead to a maximum current from 1 to 10 A depending on Ω and N (20). At present no high-current effects have yet been observed in the microtrons.

We may conclude that at present we have reached a good understanding of the microtron as a microwave machine. The unique feature of the microtron that is inherent to its principle is the high electric field at which this accelerator operates. The electric and magnetic fields in the microtron provide sufficient stability for the acceleration of electrons. The upper limit of energies is $50 \div 100$ MeV. Not all the details, especially the high-current effects in the microtron have been examined, but the present understanding is sufficient for building efficient accelerators that in this range of energies may open new possibilities both for science and industry. Although most technical problems connected with the construction of microtrons have been solved work is still to be done to attain the degree of engineering perfection reached on linear accelerators produced industrially.

We will now pass to microtrons that have successfully operated to illustrate the possibilities of these machines.

The first high-current microtron at the Institute for Physical Problems is now rebuilt (21). The most important characteristics of this and other S-band accelerators are given in Table I. The smaller microtron of the Institute for Physical Problems is at present used for experiments on megavolt electronics and for studies on fission. For experiments on the angular distribution of fragments in subbarrier photo-fission high intensity and well defined energy of the beam is crucial (22). These experiments that have led to the discovery of quadrupole photo-fission in heavy even-even nuclei, clearly demonstrate the possibilities of even a small high-intensity machine in the field of nuclear physics for studying processes with very low cross sections. The large microtron of the Institute for Physical Problems has a 5 ton magnet designed for energies up to 45 MeV

TABLE I

S - Band microtrons

N°	Institution	D cm	E MeV	N	I mA	Ω	W ton	Use
1	Institute for Physical Problems, Moscow, USSR (21)	75	15	17	35	$1 \div 2$	0.9	Nuclear physics, megavolt electronics
2	Institute for Physical Problems, Moscow, USSR (7)	110	32	28	50	$1 \div 2.2$	5	Accelerator research
3	JINR, Dubna, USSR (10)	110	30	30	60	2	4.5	Neutron production
4	Lebedev Physical Institute, Moscow, USSR (8)	60	7	10	110	1.2	2	Synchrotron injector and positron acceleration
5	Lund University, Sweden (9)	50	6.4	10	50	1.05	0.6	Sunchrotron injector
6	University of Western Ontario, Canada (4)	50	6.2	8	10	$1 \div 3$		Accelerator research and mega volt electronics
7	University College, London, England (18)	200	29	56	10^{-3}	1	20	Work discontinued

($\Omega = 3$) with a pole diameter of 110 cm. This machine at present is used for detailed studies of orbit dynamics (7). A machine similar to this in all details has been built at the Laboratory for Nuclear Physics at the Joint Institute for Nuclear Research (Dubna, USSR). The microtron operating with 30 orbits at 30 MeV and a pulse current of 60 mA works in conjunction with the pulsed fast nuclear reactor (10). The fast nuclear reactor in this case is used as a dynamic subcritical assembly with a high multiplication factor (300) and is a very efficient source of pulsed neutrons for nuclear physics research.

Much success has been found in the use of microtrons as injectors for synchrotrons. A 6.4 MeV microtron is successfully operated as an injector for the 1.2 GeV synchrotron at Lund (Sweden) (9). The microtron can operate at a pulse current up to 50 mA, although at present its useful current is limited to 20 mA by space charge effects in the synchrotron.

A 7 MeV microtron injector has been successfully built at the Lebedev Physical Institute (Moscow, USSR). This microtron has been very ingeniously used for accelerating positrons for experiments on storing particles in a synchrotron (8). The ratio of the number of positrons to the number of electrons is $5 \cdot 10^{-5}$ and the positrons occupy the same small phase volume that is characteristic for these machines. At present a double 15 MeV electron-positron microtron is built at the Lebedev Institute with a still greater conversion ratio.

The microtron seems to be very well suitable for injectors and the pertinent data on a number of accelerators are presented in Tables I and II. One of the reasons for the success of the microtrons as injectors lies in the great stability of the beam energy and the compatibility of the space phase occupied by the microtron beam and the phase space accepted by the synchrotron.

In all machines mentioned the magnetic field is uniform. Only in the London University College microtron some slight inhomogeneity was introduced into the magnetic field to obtain a certain amount of focusing. Although the current obtained on this machine is very low the experience gained in the construction of a large magnet with correcting coils is of interest for the future development of this type of accelerators.

As we have already noted, inhomogeneous magnets with edge focusing have been proposed for the microtron. An accelerator with 7 orbits of this type has been successfully operated in Canada (4). Electrons were accelerated by a cylindrical cavity and injected from an external electron gun. Experiments have shown that the design and adjustments of an edge focusing magnet are rather complicated. Extra shielding is required in the field free areas of the magnet. At present it seems that the development of focusing by the cavity in a microtron with a uniform field provides sufficient stability of the electrons without the introduction of any marked non-uniformity of the magnetic field, although it may be reasonable for a large number of orbits to introduce certain symmetrical inhomogeneities that will improve the radial stability.

Considering the future development of pulsed microtrons one can think that the major trend will be the construction of accelerators for energies up to 30-40 MeV using modern high-power microwave generators. The most suitable type of generators is the self excited magnetron or a magnetron-type amplifier directly connected with the cavity so as to form a self-excited system. In this case the resonator of the microtron will not require any special tuning, and in view of the high efficiency of these amplifiers one may expect high efficiency of the whole system. Pulsed accelerators of this type may well compete with linear accelerators. The main advantage of the linear accelerators is the possibility of transiently accelerate very large currents through the use of stored electromagnetic energy in the waveguide. In the microtron because one has to accelerate electrons by well defined energy such transient operation is impossible. The major advantage of the microtron in comparison with the linear accelerator is its outmost simplicity. We have noted the simplicity of the high-frequency system. In the high-current microtron there is no electron gun with its associated pulser. These are the basic reasons why the microtron may prove to be the best type of accelerator for these energies in the cases when extreme currents such as those necessary for pulsed neutron work are not required.

In the microtron there is a threshold power approximately 100 kW beginning with which it is possible to accelerate electrons independent of their final energy. The principal difference between the linear accelerator and the microtron is that one can consider the linear accelerator to be a series connected machine, and a microtron may be considered as an accelerator in which we have parallel connected beams passing through a single resonator with a correspondingly lower value of the characteristic impedance of the accelerator.

In its present form linear accelerators will always be a pulsed operated machine. Only by lowering the field and passing to excessive lengths such as in the Saclay linear accelerator project can one expect to operate at higher duty ratios. Another approach is the use of superconducting

TABLE II

Accelerator	E MeV	N	Beam Size mm	Divergence mrad		Phase Volume mm × mrad	
				axial	radial	axial	radial
Institute for Physical Problems, Moscov USSR (7)	30	28	1.5×3	0.5	5	$0.7 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$
Lebedev Physical Institute Moscow, USSR (8)	7	10	2×4	1.5	15	$6 \cdot 10^{-3}$	$6 \cdot 10^{-2}$
Lund University, Sweden (9)	6.4	10	7×7	2	7	$1.4 \cdot 10^{-2}$	$5 \cdot 10^{-2}$

resonators for linear accelerators. On the other hand, a CW microtron is feasible and we can expect that it can cover the energy range up to, may be, 50 MeV and prove to be powerful instrument for nuclear physics research.

Some consideration must be given to the use of cavities cooled to low temperatures in the microtron. In the first place one can attempt to use cavities of normal metals cooled to low temperatures at which the losses will be determined by the anomalous skin effect. We cannot expect to lower the power by more than an order of magnitude introducing at the same time all the complications that arise with the use of cryogenic engineering. The power gained will be lost in the low efficiency of the liquefiers and one cannot expect much in this respect although a more detailed analysis in some special cases may be profitable. It is of greater interest to consider the use of superconducting cavities. A superconducting cavity placed in a microtron with a uniform magnetic field will disturb the field to the extent that the geometry of the accelerating fields will be totally changed. With the added difficulties of heating the cavity by electrons not captured to the accelerating phases the use of a superconducting cavity in such a microtron does not seem reasonable. A superconducting cavity will be more suitable in an edge focusing magnet for one can place the cavity in the field-free part of the magnet and completely rely on the magnetic field for providing the required axial and radial focusing. In this case one can shield the cavity from any heating due to lost electrons for in a superconducting cavity such local heating may be disastrous. An accelerator of this type would be of interest only for energies higher than, say, 100 MeV that do not at present seem attainable by a straight forward development of the pulsed microtrons and the CW microtrons. The first step in developing a superconducting microtron would be the successful operation of a high-field superconducting linear accelerator.

In this review we will not further compare the microtron with other accelerators, such as electrostatic machines or synchrotrons. The simplicity and ease with which electrons may be accelerated in the microtron open a wide field for the development of this accelerator for medical, chemical, and industrial purposes that lie outside the scope of this Conference (21). We have not considered the use of a microtron for mega volt and high-power electronics. The development of this accelerator as a relativistic electron machine belongs to these domains of physics from which the microtron has emerged. Our main object was to consider the modern developments of the microtron and the future trends in its evolution.

May be on the next Conference on accelerators the microtrons will cease to be a topic in physics having fully passed into the hands of the engineers. In this case we can say that the development of the microtron as an object of science has ceased as it has become an instrument of science and industry.

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THE 30 MeV HIGH-CURRENT MICROTRON

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(Presented by S. P. Kapitza)

The design of the 30 MeV microtron in its principal features is similar to the first microtron with 12 orbits and 700 mm chamber built at the Institute for Physical Problems. The 4.5 t magnet of the larger microtron is circular with 110 cm pole pieces and a 12 cm gap. The pole pieces of the magnet are simultaneously the lids of the vacuum chamber. The accelerator is pumped by standard diffusion pumps with liquid nitrogen traps. The high-frequency system consists of a high-power fixed-frequency S-band magnetron coupled to the resonator through a ferrite circulator.

The accelerating cavity is cylindrical or rectangular. The electrons are emitted under the direct influence of the high-frequency electrical field from a lanthanum-boride emitter placed on the intter surface of the cavity. Electrons may be captured to accelerating phases in two ways. In the first mode of operation acceleration of electrons is possible for values of the magnetic field in the range from 0.8 to 1.7 H_0 where $H_0 = 2\pi E_0/e\lambda$ is the cyclotron magnetic field at the operating wave length (1070 Oe at 10 cm). In this case the increase of the energy for each turn is correspondingly 0.8 to 1.7 E_0 and $E = mc^2 =$ 511 keV is the electron rest energy.

In the second mode of electron capture the magnetic fields is 1.7 to 2.2 H_0 and the energy gain per turn is 1.7 to 2.2 E_0. For a 110 cm magnet and 30 orbits the energy on the last orbit may vary from 12 to 26 MeV for the first mode of operation and from 26 to 35 MeV for the second.

On the 700 mm microtron with 12 orbits we studied in detail the first mode of operation and showed experimentally that one can efficiently capture particles and accelerate them without any appreciable loss to the 12th orbit (1). For a larger number of orbits certain difficulties arise that are connected with disturbances from inhomogeneities of the magnetic field and the geometry of the resonator. Therefore, in the microtron with 30 orbits our main efforts were connected with studies of the dynamics of the electrons and the achievement of sufficient orbital stability, especially for the second mode of operation. For the second mode of operation these difficulties that were rather easily overcome for the first type of cavities were greater, but in this case one can accelerate particles to a higher energy.

The magnetic field of the microtron is uniform and the vertical stability is fully due to the focusing by the electromagnetic field of the accelerating cavity. Appropriate calculations show that by suitably shaping the transit holes in the cavity in the first type of motion one can rather easily obtain the necessary axial stability (2, 3).

This was experimentally shown for the larger microtron. If the entry hole had the form of a horizontal slit and the exit hole was circular or square, then the particles describe stable axial oscillations with a period of approximately four orbits. The period does not appreciably change beginning from the third or fourth orbit up to the last. In this case the axial motion is stable under the action of various perturbations, although there is no damping.

In the second mode the particles gradually drift to the edge of the entry hole where