HIGH-CURRENT MICROTRON INJECTOR*

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Analyzing the characteristics of various intermediate-energy accelerators (Van de Graaf generator, cascade generator, pulse transformer, microtron, linear accelerator and others) from the point of view of their utilization as injectors for synchrotrons, we have found the microtron to be quite promising for attaining this goal. The reasons for our choice are the simplicity of construction, high energy homogeneity and good geometric beam parameters, ease of extraction for a large portion of the accelerated electrons and compactness of this accelerator.

For the experimental verification of the theoretical premises and also for studying the new possibilities, pertaining basically to an increase in intensity, a 7 MeV microtron was built and installed (October 1961) in the laboratory of photomeson processes of the Institute of Physics imeni P. N. Levedev, Academy of Sciences USSR. The fundamental characteristics of the microtron are given below. The accelerator is described in detail in another article [1]. The magnet of the microtron (the total weight of the iron and winding is 2 tons) ensures the creation of a uniform (to within 0.3 percent) field in the 50 cm circular arc for a gap of 12 cm between the 60 cm diameter pole pieces. The maximum value of the uniform field in the gap is 4000 Oe. The power supply of the magnet is stabilized to within 0.05 percent and the required power in the operating regime (about 1000 Oe) is 450 watts. The poles of the magnet are covers for the vacuum chamber, which is built in the form of a brass ring with nine soldered connecting pieces. The vacuum pumping system consists of mechanical fore-pump and an oil diffusion pump. A vacuum of 10^{-6} mm of mercury in the operating volume of the chamber is reached 1.3 hours after the pumps are switched on.

The rf system of the microtron includes the following elements: a) a pulse magnetron oscillator operating in the 10 cm range with a repetition rate of 50 or 100 cps and a pulse duration of 3 μsec; b) a waveguide duct having a rectangular cross section of 72 x 44 mm operating at the rf fundamental H_{01};

*This report was not presented.

c) a plane cylindrical resonator similar to the one described [2] in which oscillations of the type E_{010} are excited.

The utilization of a ferrite rectifier as the matching element between the magnetron and the accelerating resonator is an important innovation in the waveguide duct of the microtron [3]. Such a modernization of the waveguide duct permits us to increase the efficiency* of the microtron by a factor of two. Here, the reduction in the total length of the waveguide duct and the decrease in the number of transition connections permits us to evacuate completely the waveguide from resonator to magnetron, thereby significantly increasing its electrical stability. In addition to the good matching between the resonator and magnetron, the ferrite rectifier permits us to regulate smoothly the value of the transmitted power and wave phase by varying the current in the windings of its electromagnet. The losses in the rectifier corresponding to maximum attenuation (20 db) in the reverse direction are about 20 percent of the transmitted power. To sum up, the addition of a ferrite rectifier significantly simplifies the construction of the microtron and improves its operational stability to a great degree.

With the aim of eliminating the effect of the heating current on the capture of the electrons in the acceleration regime [2] and also for increasing the operating lifetime, a specially constructed microtron injector was developed [1] with a cathode of lanthanum boride LaB_6 heated by a conical tungsten spiral. Such an injector requires 35 watts for a heating current of 6.5 A. While studying the conditions of injector operation, it was found that depressing the emitting surface of the cathode with respect to the internal surface of the resonator by 0.3--0.5 mm led to an increase in the coefficient of electron capture of up to a value of 0.05--0.04 instead of 0.025--0.02. Qualitatively, this effect is explained by the improvement in the system optics of the cathode-input aperture. For a current of 20--25 mA of the accelerated electrons after ten orbits, the described injector operates for about 15--20 hours where the lifetime is determined, basically, by the burning out of the heater.

Another method which has been considered by us for increasing the capture coefficient K lies in the supply of a positive cathode bias to the injector (Figure 1). Here the dependence of the cathode emission current on the phase of the rf field is approximated by a sinusoidal curve while straight lines parallel to the abscissa correspond to different values for the bias potential. Since the capture coefficient K is the ratio of the shaded area to the total area of the emission current, the suitability of the bias supply is evident from Figure 1. In our experiments, a positive bias at the cathode was produced automatically owing to charging of the heating circuit wiring capacitance to ground by the current of emitted electrons. The magnitude of the bias may be controlled accurately by smoothly varying the internal resistance of a high-voltage triode, inserted between the injector cathode and ground. For a positive cathode

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*By efficiency, we mean the ratio of the usable power required for the acceleration of the resonance electrons to the minimum power of the rf generator necessary for ensuring operational stability for the accelerator in the given regime.

bias of about 4 kV, a capture coefficient of about 0.1 is obtained. The increase in the capture coefficient automatically releases a portion of the rf power which may then be used for accelerating additional electrons. However, in order to obtain high beam currents, a significant increase in cathode emissivity is required. The joint use of the above-described methods would permit us to obtain a current value for the accelerated electrons of up to 110 mA for an energy of 6.5 MeV. However, it is not possible to consider such an intensity at the present time as being practical in view of the highly overloaded cathode operation.

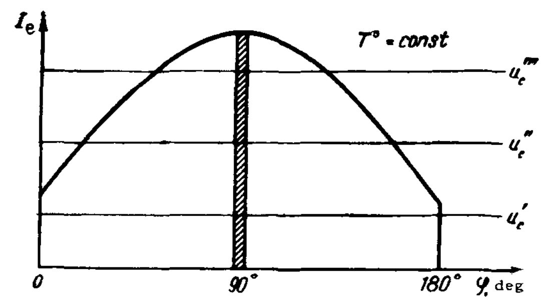

Figure 1. Dependence of cathode emission current on the phase of the rf field of the resonator. The straight lines u_c = = const indicate the action of positive bias.

A detailed analysis of the conditions for capturing the electrons in the microtron acceleration regime carried out recently permits us to determine new methods for increasing the current limit of the microtron. Calculations carried out on an electronic computer attest to the existence of capture regions for an initial nonzero electron phase and energy and at various positions of the cathode along the resonator axis. The calculation results are illustrated in Figure 2, where the boundaries of the capture regions are shown for several positions of the cathode and specific initial phases and energies. An analysis of the calculated data indicates that the horizontal dimension of the cathode may be increased up to 10--12 mm instead of the 1.5 mm used at the present time, while maintaining the capture coefficient.

In order to satisfy the initial conditions for the flight energies and angles, the emitting surface of the cathode must be recessed 0.3--0.7 mm with respect to the surface of the resonator. As an example, Figure 2 describes the electron parameters corresponding to a cathode recess depth of 0.5 mm; here, the width of the initial phase capture region is roughly constant and equal to 0.08. The deflecting field in the aperture cathode, which may substantially affect the value of the energy and flight angle for electrons in the resonator, was not taken into account in the calculations. However, as follows from Figure 2, the regions of stable acceleration overlap practically all of the possible values for the energies and horizontal angles, and, consequently, such an assumption is permissible.

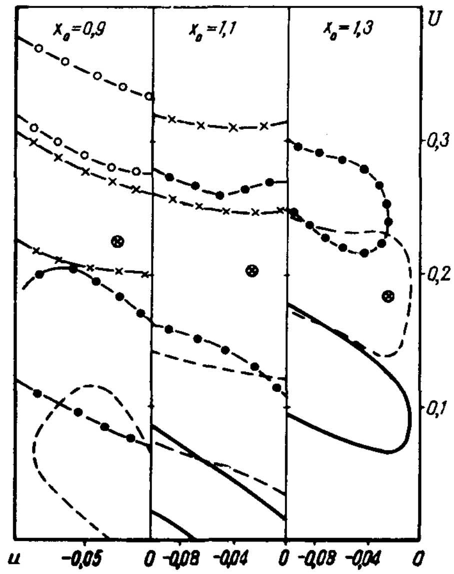

Figure 2. Capture regions according to initial phases, angles and energies, for different positions of the cathode along the resonator axis:

φ_0 = 0.0 (-); φ_0 = 0.1 (--); φ_0 = 0.2 (-●-●); φ_0 = 0.3 (-x-x); φ_0 = 0.4 (-o -o); The initial electron parameters for the case when the cathode is recessed 0.5 mm are denoted by ⊕.

In order to verify the calculations, an experiment was performed on the capture from the long cathode. The length of the cathode slit along the horizontal was 8 mm. As the first step, the "point" cathode was shifted successively to two boundary positions and to the middle of the slit. Here, the capture coefficient for all three positions turned out to be equal to 0.02. Afterwards, the "point" cathode was replaced by a horizontal band and the value for the capture coefficient remained constant. The significant deterioration in the capture coefficient for the case of a slit-shaped cathode aperture is associated with a change in the optics of the cathode-slit system. At the present, work is being performed on substituting a system of successive circular apertures for the slit. We may have confidence in the fact that the injection system developed permits us to obtain a working intensity of the order of 100--150 mA on the microtron for injector lifetimes of about 50 hours.

In experiments using the long cathode, an injector with an electronic heater was used. At the present time, there are no final data on the lifetime of such an injector; however, in view of the low heater temperature (about 2100°C), we may state that it is significantly increased. The new injector system permits us, apparently, to study the maximum current capabilities of a microtron including the effect of space charge and coherent radiation by the electron bursts.

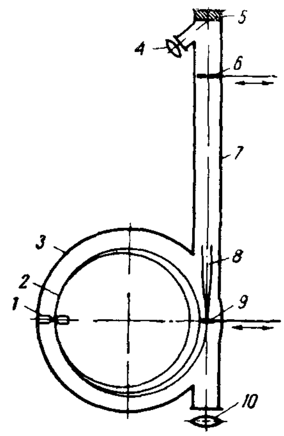

Figure 3. Diagram of the experiment to measure the angular and geometric characteristics of the beam at the output of the microtron:

1 -- accelerating resonator; 2 -- orbit preceding the extraction orbit; 3 -- chamber; 4 and 10 -- objectives of the TV cameras; 5 -- collector; 6 and 9 -- diaphragms; 7 -- adjusting tube; 8 -- extraction duct.

For investigating electron beam injection from the microtron into the synchrotron, it is interesting to give data on the geometric shape and angular characteristics of the beam. The information given in the literature is purely of a qualitative nature and is not noted for accuracy. In order to verify the geometric and angular characteristics of the beam at the output of the microtron, a series of measurements was performed as indicated in Figure 3. The diaphragm, 9, with the circular aperture permits us to select a "point" source of electrons from a section of the beam at the input to the outlet channel. A remote control allows the horizontal and vertical displacement of this diaphragm. The investigation of the angular distribution from the "point source" is carried out by the diaphragm, 6, consisting of two mutually perpendicular slits with remote position control. The current pulses from the collector, 5, and from the input diaphragm, 9, are recorded by an oscilloscope. The observation of the shape and intensity of the beam is carried out with the aid of two television cameras, 4 and 10. In the initial experiments, an ordinary extraction system was used with a soft iron collector tube having a 7 mm diameter input aperture. Here, a great effect on the shape of the output beam was seen, depending upon the point at which the extraction duct was installed. In order to evaluate this effect, calculations were carried out which showed that the beams at the preceding orbit experienced a strong perturbation as a result of magnetic field distortion by the extraction duct which led to a phase shift of $\Delta\varphi \approx 0.4$ and, moreover, gave a significant energy spread as a result of the square-law dependence of the perturbation on distance. In order to eliminate this effect, a circuit was designed and built to compensate for the current perturbations of the magnetic field. The compensator windings contained 1100 ampere-turns distributed according to the cosine law, along the diameter of the extraction duct. The results of the measurement of the angular and geometric beam characteristics at the output of the microtron using the compensation circuit are given in Figure 4, a and b. Figure 4, a shows the geometric dimensions of the beam at the input of the extraction duct and Figure 4, b shows the beam cross-section at a distance of 100 cm from the outlet point. The solid lines on the figures denote levels of identical intensity expressed in relative units. Here, the coefficient of beam output is 92 percent.

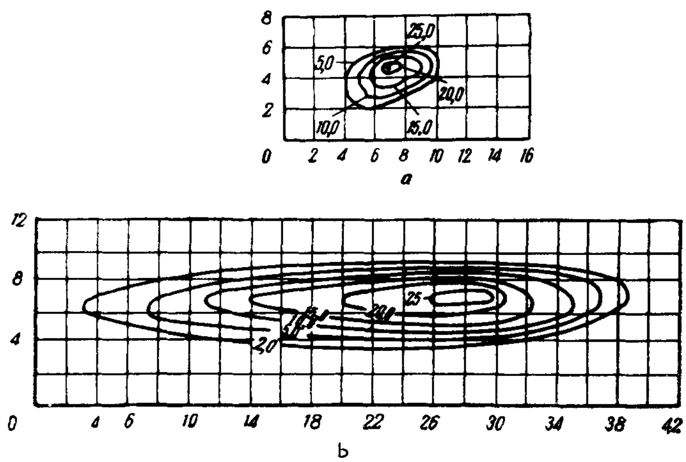

Figure 4. Cross-section of the beam at the input of the extraction duct (a) and on the collector (b). Dimensions along the ordinates and abscissas are in mm.

The results presented permit us to conclude that at the present time, it is possible to obtain electron beams at the output of the microtron with an intensity of up to 100 mA per pulse length of 2 μsec for dimensions of the output cross section of 2 x 4 mm and with a total angular spread of $1.5 \cdot 10^{-3}$ with respect to the vertical and $1.5 \cdot 10^{-2}$ with respect to the horizontal at a level of one-half the peak. The energy spread which may be obtained for an appropriate output orbit is not more than 30 keV. For these conditions, it is possible to draw a conclusion that the microtron as an injector has a high efficiency in comparison with other types of injector devices by using the general discussion on the problem of electron injection from a microtron into a synchrotron carried out in another article [1]. Preliminary experiments for the study of the possibility of injection from a microtron were carried out on the synchrotron at the Institute of Physics imeni P. N. Lebedev, Academy of Sciences USSR at an energy of 280 MeV. The experimental plan is shown in Figure 5.

In order to direct the beam into the input tube whose total length is 4 m, a focusing system of two quadrupole lenses was used while two magnetic correctors were used for amplitude control. Before striking the synchrotron converter, the electrons were in a scattering magnetic field for a considerable portion of their path. As a result of the adjustment of such a simple system of the scatterer, a beam spot was obtained having a vertical dimension of 8 mm and a horizontal dimension of 4 mm with good possibilities for controlling the dimensions and position. In these experiments, an uncompensated extractor tube was used; therefore, the intensity of the beam at the synchrotron converter was 60 percent of the intensity at the last orbit of the microtron.

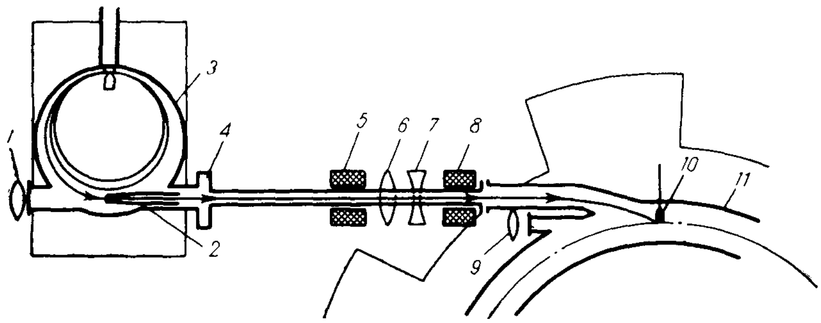

Figure 5. Diagram of electron injection from the microtron into the synchrotron:

1, 9 -- objectives of TV cameras; 2 -- tube for extracting the beam from microtron; 3 -- microtron chamber; 4 -- vacuum valve; 5 -- magnetic corrector for vertical and horizontal control; 6, 7 -- quadrupole lenses; 8 -- horizontal magnetic corrector; 10 -- scatterer; 11 -- synchrotron chamber.

Works on the study and improvement of the characteristics of a microtron as a high-current injector are being carried out. Special attention is being given to the study of the feasibility of using a microtron as a positron injector for various storage devices [4].

In conclusion, the authors express their appreciation to the staff of the photomeson laboratory: A. M. Gromov, A. V. Borisov and V. S. Malofeev, who participated in separate experiments and developments.

BIBLIOGRAPHY

1. Belovintsev, K. A., Belyak, A. Ya., Gromov, A. M., Cherenkov, P. A. Atomnaya energiya (Atomic Energy), Vol 14, 359 (1963).
2. Kapitsa, S. P., Bykov V. P., Melekhin, V. N. Zh. eksperim. i teor. fiz. (Journal of Experimental and Theoretical Physics), Vol 41, 368 (1961).
3. Belovintsev, K. A., Belyak, A. Ya., Gridasov, V. I., Cherenkov, P. A. Atomnaya energiya (in press).
4. Belovintsev, K. A., Denisov F. P. Atomnaya energiya (in press).