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ELECTRON BUNCHES IN A MICROTRON

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In continuation of previous work[3], the dimensions and shape of electron bunches in a microtron are studied. The results agree qualitatively with numerical calculations performed on an electronic computer.

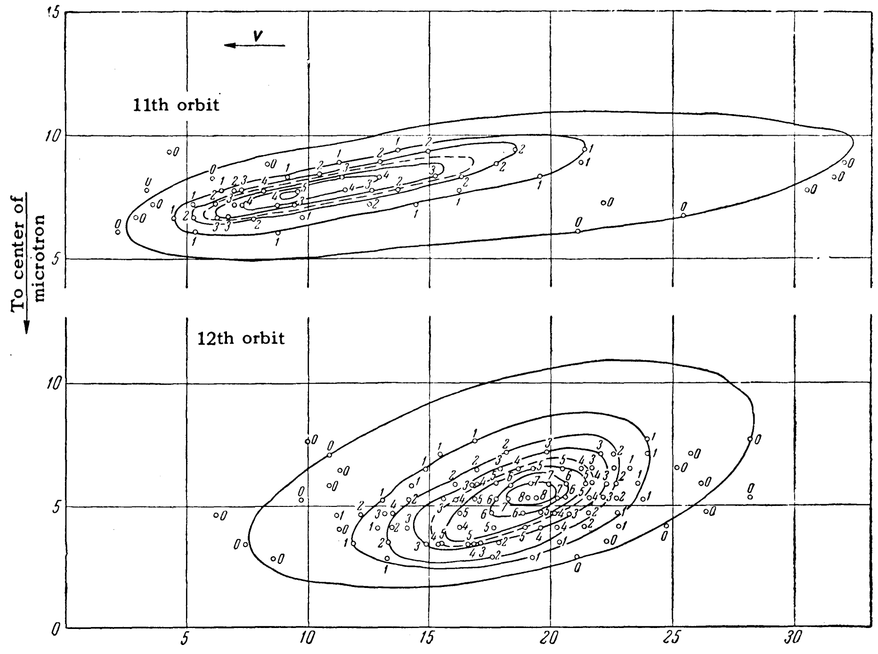
IN connection with the construction of a high-current microtron[1] we must consider the maximum current and energy attainable with this type of accelerator. The limiting parameters of a microtron are evidently determined by the collective interaction of electrons in the beam, i.e., by the coherent radiation[2] and space charge of the electron bunches. The electron distribution in a bunch must be known before the role of these effects can be evaluated correctly; this distribution has therefore been investigated experimentally.

The method of measurement described in our earlier work[3] has now been modified slightly. First, in order to measure the longitudinal and transverse beam dimensions at approximately the same orbital point a beam-limiting diaphragm was placed as close as possible to the sweep resonator; the distance from the mean position of the latter to the diaphragm did not exceed 50 mm. Second, the speed of the measurements was greatly accelerated, the results being recorded on a high-speed automatic N-110 potentiometer. The time required to measure a single bunch was thus reduced to about 10 minutes.

The experimental sequence was as follows. The microtron and auxiliary units were switched on; following a prolonged warmup period the required magnetic field was established. The accelerating resonator was then tuned accurately. Since the possible equilibrium phases of acceleration lie in a narrow interval from 0° to 32.5°, the permissible hf field amplitudes are confined to an extremely small range. It thus becomes very important to determine the amplitude correctly, although a highly accurate direct measurement would be difficult to achieve. The field amplitude was therefore determined from the beam current maximum. An operating mode with a maximum phase stable region is selected automatically, corresponding to the mode investigated in the numerical calculations.

The accelerating resonator is tuned by means of the following adjustments: a) change of the intrinsic resonator frequency by a mechanical deformation of its walls, b) change of the electric length of the waveguide transmission line by means of a phase shifter, and c) regulation of the cathode current. Constancy of the hf field amplitude during a pulse was monitored by watching an oscillogram of the beam current. A small deviation of the field amplitude leads to distortion of the square pulse. It must be noted that the current oscillogram is very sensitive to any change of the operating conditions and is actually the most sensitive indicator of stable microtron operation.

Tuning of the sweep resonator, following the tuning of the accelerating resonator, has an opposite effect on the hf system, so that the tuning of the accelerating resonator must be corrected.



Electron bunching was investigated for the first type of electron motion in the accelerating resonator[1] in the 11th and 12th orbits, where the electron energy was 6.7 and 7.3 MeV, respectively. The accelerating field wavelength was ~ 11 cm; the beam current in the different runs varied within the range 2.5–6 mA.

The figure shows typical electron density distributions in the median plane of bunches in the 11th and 12th orbits. The abscissa and ordinate represent the longitudinal and transverse bunch dimensions in millimeters. Contour lines have been drawn through points representing equal electron densities; the lines are labeled with numbers proportional to the respective densities.

The electrons in a bunch are seen to be distributed over a very large area up to 25 mm long and 6–7 mm wide. However, the greatest interest attaches to the effective dimensions, rather than to the full dimensions, of the bunches, i.e., to the region containing the bulk of the electrons. The effective dimensions were taken to be those of the portion of a bunch in which the electron density exceeded the half-maximum; in the figure these portions of the bunches are outlined by dashed lines.

In [3] we showed that an electron bunch possesses two density maxima. A subsequent investigation showed that the existence of two maxima is always accompanied by current oscillations of the microtron beam during an accelerating pulse. These oscillations result from shifts of the acceleration equilibrium phase due to inconstant field amplitude in the accelerating resonator, and can be eliminated by more careful tuning of the resonator and phase shifter. When current oscillations are absent the electron distribution in a bunch possesses only a single maximum.

In the 11th orbit the bunch was 8.4 mm long and 1.5 mm wide; in the 12th orbit the dimensions were 5.5 mm and 2.0 mm. These results were obtained in five runs with a 15–20% spread of the measurements.

Numerical calculations showed that one of the most favorable microtron operating modes is characterized by the following dimensionless parameters:[4] $\Omega = 1.1$, $\xi = 1.065$, $x_0 = 1.1$, and $l = 1.025$. The detailed investigation of this mode in calculations was followed by a successful experimental test. Here resonance electrons are those emitted by the cathode at the peak voltage of the electric field. Electrons emitted slightly earlier or later are also accelerated to the 12th orbit but undergo phase oscillations. These electrons determine the finite spatial extent of the bunch.

Electrons emitted from different points of the cathode not corresponding to $x_0 = 1.1$ do not enter exactly into resonance and experience phase oscillations. Thus the horizontal size of the cathode also affects the length of a bunch.

For the purpose of determining the dimensions and shapes of bunches by means of an electronic computer the position of the cathode and the phase of electron emission were varied somewhat; in each case the motion was computed as far as the 12th orbit. For this purpose 38 variants were studied, of which 28 represented accelerations to the 12th orbit. The results of these calculations[5] provided a basis for a qualitative picture of charge distribution in bunches which was in good agreement with experiment.

The different effective lengths of bunches in the 11th and 12th orbits resulted from the phase oscillations, which caused the bunch length to vary from orbit to orbit with a period equal to that of the phase oscillations. In our operating mode this period was about four orbits. Calculations showed that the minimum length (about 3.5 mm) of a bunch should exist in the 5th, 9th, and 13th orbits. The maximum length (about 10 mm) should be found in thd 3rd, 7th, and 11th orbits. An intermediate value of 5.5 mm was found in the 12th orbit, and a value close to the maximum (~ 8 mm) in the 11th orbit.

Since electron bunching in a microtron depends mainly on the size of the phase stable region, it can be assumed that bunching will change very little if other types of accelerating resonators are used. Changes can occur only in the ordinal numbers of the orbits where the bunch has its maximum and minimum lengths.

In addition to the phase stable region and the kind of accelerating resonator, the horizontal size of the cathode can have some effect on bunching; with increasing cathode size the bunch size should increase. Our measurements were performed with a cathode having a horizontal length of 1.5 mm.

To evaluate the electron density we also measured approximately the vertical dimension of the bunches; in the 11th orbit this is 2.5 mm, while in the 12th orbit it is 3.5 mm.[1)] The maximum current thus far attained in microtrons exceeds 100 mA during a pulse.[6] In this case the electron density is about 5×10^9 electrons per cm^3. Our investigation of bunching permits an accurate evaluation of the maximum microtron current. The effect of coherent radiative emission on microtron operation has been investigated by S. Kapitza and L. Vaĭnshteĭn,[2] who showed that the maximum current in the first mode is about 1—2 A.

In addition to coherent radiation, space charge plays an important part in the case of high microtron currents. In our experiments no effect of coherent radiation or space charge was observed. This obviously resulted from the fact that the operating current under our conditions was far below the maximum.

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1)It must be noted that the vertical dimension of a beam depends strongly on the shape of accelerating-resonator beam apertures.[7]

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