ON AZIMUTHAL INSTABILITIES OF CIRCULATING CURRENTS

I. M. SAMOĬLOV and A. A. SOKOLOV

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Experimental data are presented from which it is deduced that circulating currents are unstable and break up into clusters which are uniformly spaced in the azimuthal plane. The conditions within these clusters are such that peculiar radial phase oscillations are set up. Because of this effect, collisions with the injector or wall of the vessel cause the electrons to be efficiently captured in betatron-type instruments.

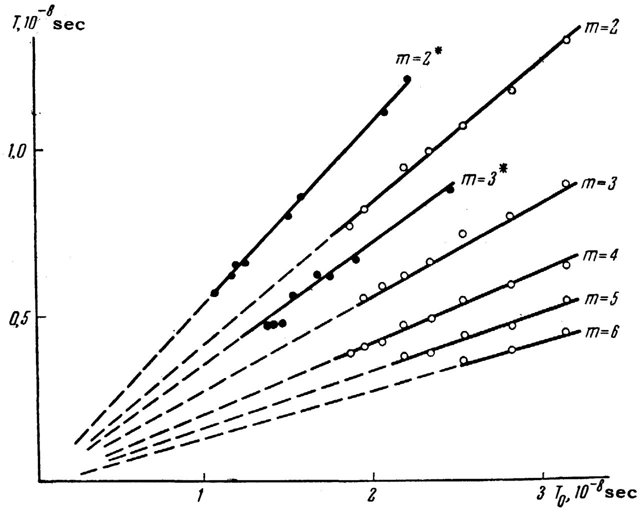
A consideration of the azimuthal effects of space charge in a synchrotron, where longitudinal interaction of particles in clusters clearly occurs, has shown that, under certain conditions, these effects can noticeably influence the motion of the particles.[1] From the report of Kolomenskiĭ and Lebedev[2] it follows that these effects must also be taken into account in other systems, because of the instability of the azimuthally uniform distribution of the beam.

The results given below have been obtained by investigating electron capture in a betatron-type device of large cross-sectional area (R_{int} = 10 cm, R_{ext} = 50 cm, effective height 10 cm) at a constant magnet-gap field $H \sim r^{-n}$, $n \sim 0.5$. A ribbon-cathode injector was used[3] and the thickness of the injector blade was 4 mm. The injection voltage pulse (U = 10 to 50 kv) was rectangular in shape and 10^{-5} sec in duration: the repetition frequency was 50 cps. By selecting a value of the constant magnetic field for a given U, it was possible to vary the radius of the instantaneous orbit, $r_i = r_0 + a$, where r_0 is the injection radius.

Using probes to investigate the current circulating in the vessel at $a/r_0 \sim 0.1$, L. N. Bondarenko and A. A. Naumov found in 1955 that a pulse of high-frequency oscillations was produced in the probes at the instant of injection. However, neither the basic laws governing these hf oscillations nor the excitation mechanism were elucidated. In our experiments we have established the following facts:

1. Maximum intensity and stability of the hf signal are observed at values of r_i which roughly correspond to the maximum of the circulating current ($a/r_0 \sim 0.1$).
2. Hf oscillations are observed over the whole range of the variables covered by the experiments, i.e., U = 10 to 50 kv and injection current J = 5 to 500 ma. At U = 20 kv, hf oscillations occur whenever J >2 to 5 ma.
3. The frequency of the oscillations is independent of J, of the pressure P in the vessel ($P = 5 \times 10^{-5}$ to 3×10^{-6} mm Hg), and of the position of the probes.
4. The amplitude of the hf signal is a maximum if the probe lies near the beam. The maximum amplitude is of the order of hundreds of volts.
5. The period of the hf oscillations is $T = \kappa T_0/m$, where m = 2, 3, 4, ... and $T_0 = 2\pi r_i/v$: $\kappa \approx 1.1$ when r_0 = 20 cm and a > 0, and $\kappa \sim 0.85$ when r_0 = 40 cm and a < 0 (see diagram). We observe that κ differs from unity because the mean energy of the particles that form the clusters differs from the mean injection energy (see below).

From the results enumerated above, it follows that part of the circulating current breaks up into electron clusters of equal density. These clusters are uniformly distributed in the azimuthal plane



Relationship between the period T of the hf oscillations and the period of revolution of the particles T_0 ($a/r_0 \approx 0.1$). The lines marked with an asterisk are obtained with r_0 = 20 cm and a > 0, and the remaining lines are obtained with r_0 = 40 cm and a < 0.

(the latter fact is a consequence of the absence of the first harmonic $T = T_0$). Actually, since a uniform azimuthal particle distribution is unstable,[2] the electrons must group themselves in condensed clusters. Since the neighboring particles in the azimuthal plane are attracted to the cluster, this process will continue until the force acting on them changes sign owing to the effects of particles left behind. It is clear that these particles can form one more or several more self-sustaining clusters, which indeed explains the absence of the first harmonic $T = T_0$.

The occurrence of azimuthal non-uniformities of the circulating current can have an important effect on the capture efficiency in betatrons. Since, for weakly-focused systems, $d\omega/dW < 0$ (ω is the rotation frequency and W the energy of the particles), and since the azimuthal component E_θ of the field of a cluster changes sign at the center of the cluster, it is evident that conditions exist in the cluster for the occurrence of unique radial-phase oscillations of the particles. If the injection current is sufficiently large, noticeable condensation of clusters occurs even after a few revolutions. Also, the constituent particles "separate" according to their radial position and energy [when $r_i = 20$ cm, $U = 20$ kv, $n = 0.5$, and $E_\theta = 1$ to 5 v/cm, the change in r_i (for electrons) is 0.6 — 3 mm within 5 revolutions]. The first particles to be lost by collision with the injector or the walls of the vessel are those whose instantaneous orbits lie nearest to the injector or walls. As a result of the loss of these particles, the mean energy and mean orbit radius of the remaining part of a cluster increase (in the case of internal injection) or decrease (external injection), and some part of the cluster is trapped after a number of collisions. Under conditions of continuous injection, the injected electrons should group themselves near the clusters formed in the initial instants of injection, i.e., the clusters must condense until a dynamic equilibrium is established between the particles that are being injected and those lost. This argument is supported by the constancy of the frequency and amplitude of the hf oscillations over the flat part of the injection pulse.

It is an interesting fact that the circulating current (recorded by a Rogovski coil) and the hf oscillations of the same frequency are observed long after the trailing edge of the injection pulse (up to hundreds of microseconds at $P = 5 \times 10^{-6}$ mm Hg). The strengths of these oscillations and of the circulating current are 10 to 30% of the corresponding values at the instant of injection, and decrease more rapidly with time with increasing pressure. (Currents occurring after the injection pulse are discussed also by Ivanov, Komar, and Korobochko.[4])

In concluding we note that the capture mechanism proposed above, based on a longitudinal interaction of the electrons, may prove more effective than the mechanism associated with transverse interaction of the particles in the beam.[5,6] Information on the relative efficiencies of these mechanisms can be obtained experimentally by using an injector mounted above the plane of the equilibrium orbit.[6]

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