EXPERIMENTAL INVESTIGATION OF A HIGH-FREQUENCY INSTABILITY IN AN ION BEAM INTERACTING WITH AN ELECTRON BACKGROUND

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An investigation has been made of the interaction between a proton beam and an electron background which compensates the space charge of the beam. The electron velocity is of the order of the thermal velocity while the ion beam is accelerated by a voltage of several tens of kilovolts. It is shown experimentally that coherent oscillations can be amplified in the direction of the beam motion because of a high-frequency instability that arises in the ion beam.

INTENSE ion beams are used for various technical purposes. It is important under actual conditions that the space charge of the ion beam in a given device be compensated by an electron background, which is usually formed by ionization of the residual gases by the ion beam. Situations of this kind have been discussed by Faĭnberg[1] Nezlin[2] and others.

By analogy with a model given by Pierce,[3] it can be shown that an ion beam whose space charge is compensated by an electron background is subject to a high-frequency instability. The simplest case arises in a one-dimensional geometry without a magnetic field. A more complicated case arises when the electron background is magnetized. Attempts have been made to observe experimentally the generation of oscillations due to this kind of instability in ion beams with the purpose of relating the frequency of oscillation to the plasma frequency of the electron background used to compensate the space charge of the ion beam.[4] These experiments have shown that the oscillation frequency corresponds to the electron plasma frequency, which was measured independently by observing the phase shift in a cavity resonator.

However, investigations of an instability under conditions of self-excitation are always complicated and the results are more indefinite than in the case in which the instability is used for amplification of a coherent high-frequency signal of a specified frequency. By investigating a convective instability in the amplification mode it is possible to observe the instability in pure form, without the complication due to feedback and resonances. The present experiment consists of the measurement of the threshold amplification (dB/m) in a proton beam in which the space charge is compensated by an electron background.

In the one-dimensional approximation a system consisting of an electron background which is penetrated by an ion beam can be described by the following dispersion equation:[5]

$$\frac{\omega_{pi}}{(\omega/k - v_i)^2} + \frac{\omega_{pe}}{(\omega/k)^2 - c_e^2} = k^2, \tag{1}$$

where ω_{pi} and ω_{pe} are the ion and electron plasma frequencies, is the working frequency, k is the propagation constant, v_i is the velocity of the ion beam and c_e is the electron thermal velocity.

The imaginary part of the propagation constant determines the gain factor for the system G:

$$G = 10z \lg e \cdot \mathrm{Im}(k), \tag{2}$$

where z is the distance measured along the axis of the beam.

Using this equation we can estimate the gain G as a function of the density of the ion current j. The frequency region and the operating voltage are taken in accordance with the experiment. In the calculation it is assumed that the ion beam is compensated by electrons. The thermal velocity of the electron background was not measured in the experiment. For this reason Eq. (1) is solved for two cases: $c_e = 0$ and $c_e = 2 \times 10^6$ m/sec (which corresponds to an electron thermal energy of approximately 10 eV). If we assume $c_e = 0$, the solution of Eq. (1) is simplified considerably. In this case we find

$$k = \frac{\omega}{v_i} \pm j\frac{\omega_{pi}}{v_i}\left[\left(\frac{\omega_{pe}}{\omega}\right)^2 - 1\right]^{-1/2}. \tag{3}$$

Equation (3) shows that the initial fluctuations in the ion beam can be amplified at all frequencies below the electron plasma frequency.

In Fig. 1 we show the gain G as a function of the current density j computed for the case $c_e = 0$ with an accelerating voltage of 65 kV ($v_i = 3.5 \times 10^6$ m/sec) for several values of ω (125, 220, 280 MHz). These curves determine the range of current densities for which amplification of high-frequency instabilities occurs in the ion beam. It is interesting to note that the gain is a weak function of the current over a wide range of values; this is the case because a change in current in the compensated beam implies a simultaneous change in the ion and electron plasma frequencies.

Curve 2a in Fig. 1 is computed for the same values of the parameters as curve 2 but with $c_e = 2 \times 10^6$ m/sec. It is evident from a comparison of these curves that taking account of the thermal velocity of the electron background removes the singularity at the point $\omega = \omega_{pe}$; it also leads to a significant reduction in the gain at points close to resonance and to a reduction of the order of 1.5 dB on the sloping portion of the curve.

The experiments were carried out with an ion beam in which the voltage could be varied from 40 to 80 kV

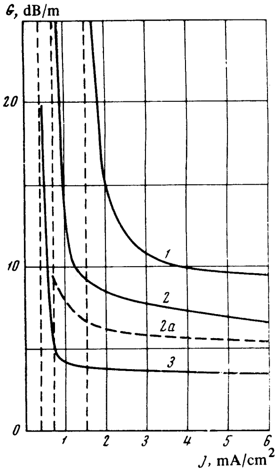

FIG. 1. The gain as a function of current density (U = 65 kV). Curves 1–3 are computed $c_e = 0$ for ω equal to 280, 220 and 125 MHz respectively. Curve 2a is computed for $c_e = 2 \times 10^6$ m/sec with $\omega = 220$ MHz.

and the current from 1 to 10 mA. The beam diameter was varied from 1 to 4 cm and was uniform over a length of about two meters.

A diagram of the experimental arrangement is shown in Fig. 2. The proton beam passes through two couplers. The first serves for preliminary modulation of the beam. A signal from a high-frequency source is applied to this coupler. The second coupler is used to measure the high-frequency signal along the beam. The system allows for movement of the second coupler in the beam direction over a distance of approximately 150 cm. The high-frequency signal in the detection coupler is measured by means of a high-frequency detector and an indicator (a milliammeter or an oscilloscope, depending on the signal level). The detection coupler consists of a section of a helix designed for maximum coupling between the electromagnetic wave and the beam. The helix diameter is 6.7 cm, the pitch is 2.5 mm, and the length is 20 cm. With these dimensions the optimum frequency range for the interaction between the electromagnetic wave and the ion beam lies in the range 20 to 40 MHz. The synchronism condition between the retarded electromagnetic wave and the beam is reached at 65 kV. Two magnetic lenses are used to provide for additional focusing of the beam. The ion beam is produced in a vacuum volume which is pumped to a pressure of 10^{-5} mm Hg. Under these vacuum conditions it can be assumed that the ion beam is compensated by electrons that are produced by ionization of the residual gas.

These experiments show that no high-frequency signal is observed in the detection system in the absence of the beam. When the beam is switched on a high-frequency signal is observed in the detection system and, in the majority of experiments, the magnitude of this signal increases as the detection system is moved toward the collector. In Fig. 3 we show typical curves that characterize the signal growth along the beam. Along the abcissa we have plotted the distance of the detection system with respect to the initial position. Along the ordinate axis we have plotted the amplification with respect to the signal at the initial position of the detection system. It is evident from these curves that the signal in the detection system increases as it is moved over a distance of 120 cm. The signal growth is a sensitive function of the operating conditions in the device which produces the ion beam (the system used for forming and focusing the beam). For this reason it is reasonable to assume that the gain depends on the beam configuration. Rough estimates of the diameter of the beam are obtained by making measurements of the transmission of the beam through metal tubes. A rough picture of the beam configuration can be obtained visually from the emission due to residual gases in the chamber and from the change of current at the collector. The experiments show that as the current is increased the diameter of the beam increases to some extent but that the beam remains parallel over a length of approximately 2 meters, expanding somewhat in the direction of the collector.

Special experiments were carried out in order to determine the effect of the beam configuration on the gain: both the modulation coupler and the detection coupler were moved along the beam while the distance between them remained fixed. In this case all changes in signal can be attributed solely to the change in the beam configuration. In Fig. 4 we show curves taken for various currents that characterize the gain in the direction of the beam. It is evident from the curves that under these experimental conditions there is a small gain or attenuation of the signal (± 1.5 dB), depending on the current and the focusing conditions. These curves were taken at a frequency of 35 MHz. Similar curves are obtained at other frequencies. The performance of the frequency measurements is complicated by the fact that the modulation and detection systems both exhibit frequency sensitivity, because of imperfect matching. The effect of gain along the beam

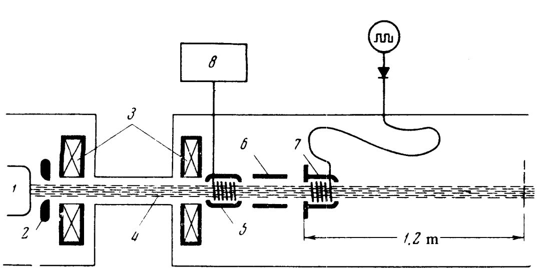

FIG. 2. Block diagram of the experiment: 1) ion source, 2) defining iris, 3) magnetic lenses, 4) proton beam, 5) modulation system, 6) deflection plates, 7) detection system, 8) high-frequency source.

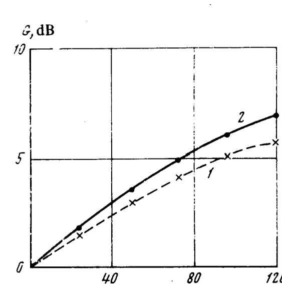

FIG. 3

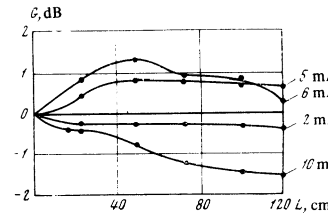

FIG. 4

FIG. 3. The gain of the high-frequency signal in the detection system as a function of position. I = 5 mA, U = 65 kV, f = 35 MHz; curve 1) $P_{in} = 0.4$ W, curve 2) $P_{in} = 4$ W.

FIG. 4. Gain the detection system when both systems are moved along in the beam.

is observed at a number of frequencies (determined by the antenna sensitivity) in the range between 20 and 70 MHz. The resonance peaks predicted by Eq. (3) are not observed. The observed magnitude 5–6 dB/m is in accordance with the calculated gain value on the sloping portion of the curve (curve 2, Fig. 1). A more detailed comparison of the experimental results and the theory is difficult because of the lack of data on the diameter and structure of the beam.

A general tendency can be noted. This is the appearance of gain at higher frequencies with increasing current, in accordance with the curve in Fig. 2. At currents of 1–2 mA gain is observed at frequencies up to 43 MHz, while at currents up to 10 mA gain is observed at frequencies up to 63 MHz.

In order to demonstrate the effect of the electron background, deflection plates are used, these plates being located beyond the modulating system. Voltages up to 500 V are applied to these plates. When these plates are energized some of the electrons are lost from the interaction space. This effect leads to a reduction in gain. In Fig. 5, curve 2 characterizes the reduction in gain when the plates are switched on as compared with curve 1 for the plates switched off. Since the length of the proton beam is bounded in these experiments, in order to increase the high-frequency power in the beam the input power applied to the modulating system must be increased. The curves in Fig. 3 are taken for various input powers: curve 1 corresponds to an input power of 0.4 W and curve 2 to a power of 4 W. As the input power is increased the high-frequency power in the beam is increased but the general nature of the curves is not changed.

In the future it will be important to determine whether or not a saturation appears in the development of the high-frequency instability in the ion beam as predicted by Friedberg.[6]

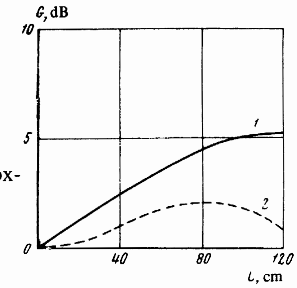

FIG. 5. The gain of the rf signal in the detection system as a function of position. Curve 1 is taken with the deflection off. Curve 2 is taken with approximately 500 V (positive) applied to the plates.

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