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OBSERVED DISRUPTION OF INTENSE RUNAWAY ELECTRON STREAMS*

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Properties of intense interpenetrating streams of ions and energetic electrons were first investigated theoretically by Bennett.[1] Following suggestions by Budker[2] concerning the possible practical importance of self-focusing relativistic electron streams, experiments aimed at producing and investigating such streams were begun in several laboratories.[3-7] So far these attempts have not succeeded in producing intense, stable self-focusing streams.

One method of attacking the problem is to apply a "strong"[8] betatron electric field to a plasma in a doughnut chamber and thereby accelerate runaway electrons to high energies within the plasma. The first experiment of this kind,[5] carried out at CERN, succeeded in producing currents of the order of only one ampere of stable, relativistic runaway electrons. The number of runaway electrons increased with the accelerating electric field. An experiment similar to the one at CERN except for a larger electric field (up to 180 V/cm as compared with 20 V/cm) is currently in progress at this laboratory.[9] Preliminary results show that intense runaway electron streams are produced, but that disruption of the stream occurs shortly after its formation. In the process the runaway electrons give up energy within the plasma.

One pulsed operation of the apparatus is indicated in Fig. 1. The betatron is supplemented by a longitudinal magnetic field B_φ which is turned on first, rising to a maximum (of up to 1500 gauss) in about 1 msec. B_φ is nearly constant during the plasma formation—achieved by inductively coupling rf power into the gas—and the subsequent application of the betatron electric field E. Plasma switches[10] in the betatron circuit have a closing time of about 0.1 μsec. While the circuit is allowed to ring, all observations are made within the first quarter-cycle which lasts about 2 μsec.

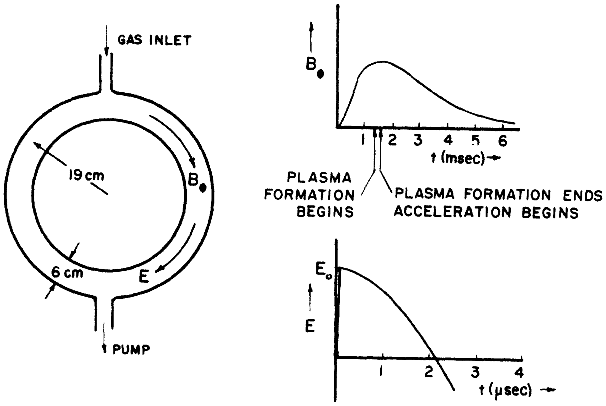

FIG. 1. The operation of the plasma betatron apparatus.

So far observations have been made on the current circulating around the doughnut and the x rays produced when runaway electrons strike the glass walls of the doughnut. The current is measured by a shielded Rogowsky coil placed around the doughnut. X rays can be observed simultaneously in two scintillation detectors placed side by side. By inserting lead absorbers in front of one of the detectors, information on the energy of the x rays can be obtained.

Experiments have been performed with argon gas at pressures of about 10^{-4} mm Hg. The degree of ionization at the moment the betatron field is applied can be varied over a wide range up to about 10 % by controlling the rf voltage.

If the electrons were accelerated normally, the current should reach a maximum at the end of the first quarter-cycle of the betatron field. The kind of results actually observed are shown in Fig. 2. The current reaches a maximum at about 0.4 μsec and then decreases to practically zero at about 0.6 μsec. Peak currents up to several kiloamperes have been observed. X rays are detected during the decrease of the current. Absorption measurements indicate that the x rays are produced by electrons, most of which have energy around 100 keV. If normal acceleration took place, the energy should have been three or four times greater. Thus it is clear that the runaway electrons lose energy within the plasma prior to striking the chamber walls.

The number of runaway electrons is not known with certainty since its determination depends on the velocity distribution of the stream. If it is assumed that the electrons accelerate normally during the initial rise of the current, the beam density can be calculated. The observed rate of increase of current—dependent on the degree of ionization—then implies ν values from 0.02 to 0.2 ($\nu = Nr_0$, where N is the number of electrons per unit length of stream and r_0 is the classical electron radius). In addition, the information from the scintillation detectors provides a rough determination of the electron density in the x-ray-producing stream, provided the velocity distribution is known. If a monoenergetic stream is assumed, ν values deduced from the observed x rays are about an order of magnitude lower than those based on the initial current. Taken altogether, the results are consistent with the following description of the behavior of the runaway electron stream: After an initial normal acceleration the electrons are slowed down, thus reducing the current and causing the stream to move away from the equilibrium betatron orbit; x rays are produced when the more energetic fraction of the stream strikes the walls.

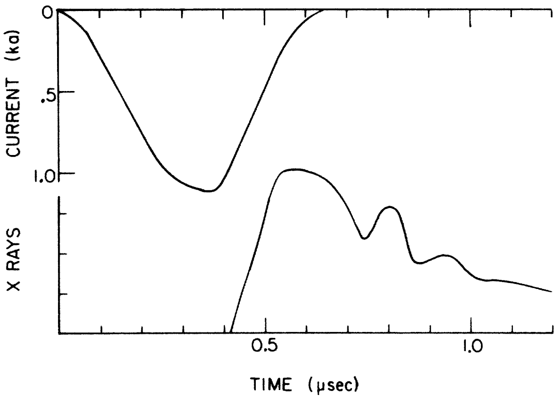

FIG. 2. Observed current and x rays (without lead absorber). For this case $E_0 = 45$ V/cm, $B_\varphi = 1000$ gauss; the initial rate of rise of current implies $\nu = 0.1$.

The observed results cannot be explained in terms of ordinary collisions between particles. Binary collisions between electrons and ions should be unimportant since the electric field is "strong" in this sense.[8] On the basis of scant available data,[11] collisions between electrons and neutral atoms can be expected to affect only a small fraction of the runaway electron stream during the times of interest. As an experimental check on this conclusion, the pressure was varied by about an order of magnitude without any significant change in the kind of results observed. Consequently it seems clear that some form(s) of collective interaction must be responsible for the disruption of the runaway electron stream.

One form of collective interaction which has been given some consideration is the two-stream instability which involves the rapid growth of longitudinal plasma oscillations. Buneman[12] has shown that this instability can be expected eventually to disrupt streaming in an infinite plasma. In the case of a finite plasma, it has been found[13,14] that while there is always an interval of instability initially, the streaming of accelerated electrons should not be significantly affected provided the accelerating field is sufficiently large or the beam density is sufficiently small. For a plasma consisting of stationary ions and runaway electrons, streams with ν values larger than those reported here are expected to escape disruption under the conditions of the experiment. However, the presence of slow electrons drastically increases the susceptibility to disruption. For example, it is only necessary to add about 1 % of stationary electrons to the plasma in order to produce (expected) disruption for the entire range of ν values investigated experimentally. The theory for this rather unrealistic case of stationary electrons mixed in with the ions and runaway electrons leads simply to predictions concerning the critical beam density, the oscillation frequencies which are strongly amplified, and the time at which stream disruption should occur. Of these there is so far only rather indirect experimental evidence concerning the latter. If stream disruption is assumed to occur at the turnover of the current wave form, the time of occurrence is found to be independent of ν and inversely dependent on E_0, whereas the idealized theory predicts independence of E_0 and proportionality to $\nu^{-1/2}$. It is not known whether or not a more realistic velocity distribution could bring the theory into agreement with experiment.

While the mechanism for stream disruption remains unidentified, it is interesting that in the process electrons give up energy within the plasma. One hopes that a relatively efficient transfer of energy from the runaway electrons to the ions is involved. Since deficiencies in the electron energies of the order of several hundred keV must be accounted for, it is possible that the ions are heated up to an interesting temperature. Experiments aimed at determining the ion temperature are being planned.

The stream behavior reported here resembles somewhat the observations made by Smullin and Getty[15] in an experiment using a pulsed electron beam. Even though the beam intensity and energy employed by these workers was orders of magnitude smaller than those of the runaway electron streams studied here, interesting beam-plasma interaction did occur.

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LINEAR POLARIZATION OF THE 3200-Mc/sec RADIATION FROM SATURN

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After the discovery by Sloanaker[1] of intense 10-cm radiation from Jupiter, measurements at 980 Mc/sec by Radhakrishnan and Roberts[2] demonstrated that Jupiter is a linearly polarized radio source. In view of these results, during the period August-October 1962, we made observations at 3200 Mc/sec to search for linear polarization in the radiation from Saturn. The purpose of this note is to report the results of these observations, which indicate that the decimeter radiation from Saturn is linearly polarized.

The data were taken with a solid-state maser amplifier mounted at the focus of the Naval Research Laboratory 84-foot radio telescope. The receiver output fluctuation level was less than 0.02°K rms for the 7-second integration time used throughout the observations.

Our data consist of drift curves; the antenna