"Runaway" Electrons and Cooperative Phenomena in B-1 Stellarator Discharges*

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Examination of the temporal distribution, relative intensity, and maximum energy of x-rays above 30 kev emanating from the B-1 stellarator during a pulsed discharge has revealed a number of interesting phenomena. The x-rays are assumed to be produced by "runaway" electrons when they strike the wall. Spuriously large pulse heights have been observed. The x-rays abruptly appear early in the discharge, before the Kruskal instability can occur. Depending on the operating conditions, x-rays can be observed at any time during the discharge except when the current is at the Kruskal limiting value. If the longitudinal electric field used for ohmic heating is "crowbarred," x-rays can appear afterwards in copious quantities; furthermore, the discharge current can decay in abrupt steps correlated in time with bursts of x-rays. The hypothesis that the current in these steps is due entirely to runaway electrons is consistent with the data. These observations are taken to be evidence for the existence of cooperative phenomena, or collective motions which can affect both the confinement and the heating of a plasma. In addition, intense nonthermal microwave noise has been detected at times correlated with x-ray emission.

I. INTRODUCTION

An accompanying paper[1] has described the general characteristics of discharges in the B-model stellarators with the figure eight geometry. From the data presented, it is clear that the ohmic heating process in these machines is not entirely understood. In the belief that they would provide a useful diagnostic tool, a detailed investigation of the runaway electrons in helium discharges was begun. In addition, it was thought that the characteristics of the discharge itself might be influenced by the presence of runaway electrons.

Runaway electrons will arise when there exist an electric field and a density such that some electrons, those faster than a certain critical velocity, will gain more energy from the field than they lose by collisions. Since the collision cross section decreases with energy, these electrons then follow the lines of force around the stellarator and continue to gain energy as long as a longitudinal electric field exists. Because of the rotational transform, the maximum energy to which these electrons may be accelerated is determined by the drift across the lines of force in one of the 180° curves of the stellarator. For the B-1 device, this limiting energy is about 3 Mev at 30 kilogauss.

Direct observation of the runaway electrons themselves is exceedingly difficult. Therefore, the thick target bremsstrahlung radiation (x-rays) produced when these electrons strike the walls has been observed. Under certain conditions the emission of x-rays is accompanied by microwave generation at power levels much greater than expected from thermal radiation.

This paper will describe measurements of the energy and intensity of the x-rays as functions of time during the stellarator discharges. These include x-rays appearing during the early stages of the ohmic heating pulse, and those occurring after abrupt termination of the heating field. It will be apparent that the x-ray emission pattern cannot be explained on a single particle model and that cooperative phenomena[2,3] must be present.

II. INSTRUMENTATION

An aperture limiter consisting of a piece of 0.05 cm thick tungsten with a 3.2 cm diameter hole centered on the magnetic axis was placed perpendicular to this axis. This provided a known cross section for the discharge and served as a high Z target which all the runaway electrons leaving the discharge region must strike. The x-rays produced at the aperture limiter were observed at 90° to the electron beam, through a glass window with a transmission of about 50% for 30 kev x-rays.

The x-rays were detected using standard scintillation counter techniques. A Dumont 6292 photomultiplier tube and a NaI (Tl) crystal, 5 cm in diameter and 5 cm thick, served as the detector, which was placed about 5.5 m from the limiter; it was shielded by 7.5 cm of lead on all sides. Collimators of various diameters were inserted in front

* Supported by the U. S. Atomic Energy Commission under Contract AT(30-1)-1238 with Princeton University.
[1] Coor, Cunningham, Ellis, Heald, and Kranz, Phys. Fluids 1, 411 (1958).
[2] L. Spitzer, Jr., Phys. Fluids 1, 253 (1958).
[3] L. Spitzer, Jr., Nature 181, 221 (1958).

of the crystal to adjust the counting rate, and absorbers were used to remove the low-energy portion of the spectrum. The cathode follower output of the detector was fed to a nonoverload linear amplifier, and the individual x-ray pulses were displayed on an oscilloscope screen. Slow oscilloscope sweep speeds (10–2000 μsec/cm) were used to observe the gross time dependence of the x-ray intensity, while fast sweep speeds (2 μsec/cm) were used when individual x-ray pulses were studied. Energy calibrations were made with radioactive sources of known energy (Cs^{137} and Co^{60}). X-ray energies were measured from the calibrated linear relationship between vertical deflection amplitude and x-ray energy.

Some coincidence measurements were made using two detectors aimed at the limiter; each was shielded by 7.5 cm lead on all sides. The resolving time of the coincidence circuit[4] was 0.1 μsec; accidental coincidences were evaluated by the insertion of a 0.4 μsec delay line in one channel. Tests with radioactive sources were made to insure that the resolving time was independent of the counting rate and the presence of the delay line. The resolving time was determined both by measuring random coincidences from two intense, uncorrelated radioactive sources, and by a measurement using two pulses which could be delayed with respect to each other.

Observations of microwave noise were made with a superheterodyne receiver at about 35 000 Mc. The 30 Mc intermediate-frequency amplifier band width was 8 Mc; no image rejection was used. The sensitivity was sufficiently low that the receiver was not saturated by the intense signal observed. Exploratory work was done using wave-guide crystal-mount video detectors which were sensitive over broad frequency bands centered at 9000, 35 000, and 70 000 Mc.

III. NORMAL DISCHARGE MEASUREMENTS

The behavior of the current as a function of the ohmic heating field at a pressure of 5×10^{-4} mm-Hg is shown in Fig. 6 of the accompanying paper.[1] The two distinct modes of current rise typical of low and high heating fields will be called Mode A and Mode B, respectively. At low heating fields (0.06 v/cm) the current rises to an initial plateau of about 500 amp and after approximately 3 msec increases to 2200 amp (at 27 kilogauss), the Kruskal limiting

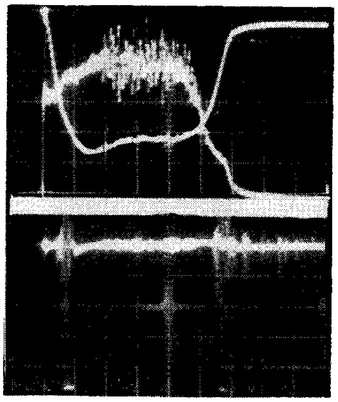

FIG. 1. Oscilloscope traces of plasma current, heating field, and x-rays. Sweep speed: 200 μsec/division. Confining field: 24 kilogauss. Pressure: 1×10^{-3} mm-Hg.

(kink instability) current[5] for a 4.1 cm diameter geometrical aperture (for this picture no aperture limiter was used); this is Mode A. With increasing heating field, the amplitude of this first current plateau increases, whereas its duration decreases. At heating fields higher than 0.1 v/cm, this plateau disappears, and the current rises smoothly to the Kruskal limiting value; this is Mode B. At higher pressures, higher heating fields are required to obtain similar discharge characteristics.

Typical current and x-ray emission patterns for a high heating field (Mode B) are illustrated in Fig. 1. It can be seen that x-rays are emitted during the smooth current rise to the Kruskal limiting current; in the low voltage case (Mode A), they are emitted during the first current plateau. They are not emitted while the current is at the Kruskal limiting value but again appear in the later stages of the discharge when the current decreases. This section will consider those x-rays emitted in the early stages of the discharge.

A. Energy Measurements

The energies of the x-rays were measured to determine whether the maximum energies were consistent with the ohmic heating fields applied. Since the x-rays observed were produced by thick target bombardment, it was felt that little significant information could be obtained with regard to the electron energy distribution; only the maximum energies observed had significance. The counting rates were reduced by collimation and absorption. Only those x-ray pulses which were undistorted and clearly separated from adjoining ones were used to

[4] R. L. Chase, Brookhaven National Laboratory Rept. No. 263 (1953). This circuit was modified by H. Miller and E. Goldberg of Project Matterhorn (unpublished).

[5] Kruskal, Johnson, Gottlieb, and Goldman, Phys. Fluids 1, 421 (1958).

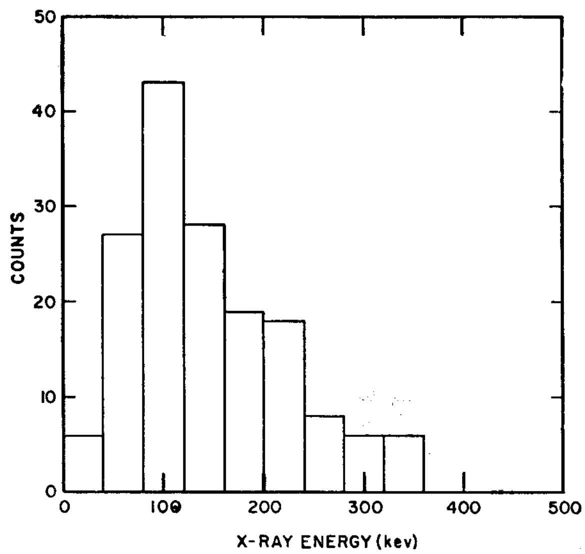

FIG. 2. Energy distribution of x-rays observed in the interval 240 to 260 μsec after application of heating field. The calculated maximum energy is 420 kev. Heating field: 0.12 v/cm. Confining field: 26.5 kilogauss. Pressure: 4×10^{-4} mm-Hg.

obtain the energy distribution. Figure 2 shows a histogram of the number of x-rays *versus* energy for an applied heating field of 0.12 v/cm, a confining field of 26.5 kilogauss, and a pressure of 4×10^{-4} mm-Hg; the x-rays were counted during the interval between 240 and 260 μsec after the heating field was applied. At this time the current (Mode B) had risen smoothly to a point just below its maximum value. The peaked distribution resulted from the absorbers used to discriminate against the low-energy end of the x-ray distribution. If the measured heating field is integrated over 260 μsec, the maximum possible energy of a single electron is calculated to be 420 kev, in agreement with the observed maximum energy. It is thus probable that some electrons were confined and accelerated from the time the heating field was first applied.

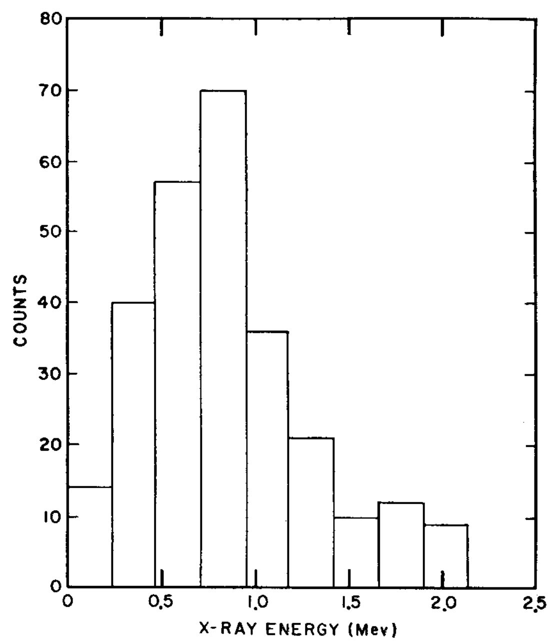

FIG. 3. Energy distribution of x-rays observed in the interval 840 to 860 μsec after application of heating field. The calculated maximum energy is 1.35 Mev. Heating field: 0.068 v/cm. Confining field: 26.5 kilogauss. Pressure: 4×10^{-4} mm-Hg.

Figure 3 shows a similar histogram obtained under the same conditions, for a lower heating field, 0.068 v/cm (Mode A). These x-rays were emitted at the end of the first current plateau, between 840 and 860 μsec after the heating field was first applied. The maximum predicted energy is 1.35 Mev; however, considerably higher energies were observed. Since the counting rates were quite low, and only undistorted x-ray pulses were analyzed, the observed intensity of high-amplitude pulses cannot be attributed to random pileup. If correlated emission of x-rays occurred, caused by a group of runaway electrons striking the limiter in a time interval short compared with the 0.2 μsec rise time of the detector, the detector would not be able to distinguish the individual events but would sum them to give a spuriously high amplitude. To test for this correlated emission of x-rays, the coincidence arrangement described previously was used. The ratio of real to accidental coincidences, using the delay line insertion technique, was found to be 2.9 ± 0.2. Thus correlated emission of x-rays from the limiter, in time intervals less than 0.1 μsec, the resolving time of the coincidence circuit, does occur; this is evidence that discrete groups of runaway electrons strike the limiter. However, the possibility of unexpectedly high electron energies, perhaps due to in-phase acceleration by local electric fields, cannot be ruled out. Further experiments are required to clarify this point. Both correlated emission and anomalously energetic electrons are indicative of the occurrence of cooperative phenomena.

B. Time Measurement

The emission of x-rays during the rise of the current begins rather abruptly. It appears, for two reasons, that the abrupt start is due to some sort of internal disturbance in the discharge which suddenly begins to carry runaway electrons to the limiter.

First, the abrupt start cannot be caused by electrons first reaching the detector threshold; the latter is about 30 kev, whereas energies over 100 kev are possible at the beginning of emission if acceleration began when the heating field was first applied. Moreover, as the magnetic field is increased with the heating field kept constant, the emission begins later, when the energies are presumably higher; hence it is not a matter of detector threshold. Second, the abrupt start cannot be caused by electrons first reaching too high an energy to be confined by the magnetic field, because electrons over 2 Mev have been observed to be confined by a 26 kilogauss field. At the time of emission the electrons have had time to be accelerated to at most 300 kev; only a small fraction of the runaway electrons near the edge of the discharge can lose confinement at that energy, and at any rate one would expect the onset of emission to be more gradual.

To see whether the x-ray emission is related to a current-dependent instability, the value of plasma current at the onset of x-ray emission was plotted and is shown in Fig. 4 as a function of heating field, for several values of confining field, at a pressure of 1.5×10^{-3} mm-Hg. Figure 5 shows similar plots, under the same operating conditions, for the plasma current at the end of the x-ray emission period. It can be seen that the behavior of the two sets of data is very similar. For both cases at the higher heating fields (Mode B), these currents, plotted as functions of heating field, appear constant at values which depend on confining field. At the lower heating fields (Mode A), the behavior is entirely different; there is now a marked dependence of these currents on heating field, but little dependence on confining field. The x-ray emission starts during and ceases at the end of the first current plateau; thus there is no significant difference in the magnitude of the currents at the beginning and end of x-ray emission. Indeed the magnitude of the first current plateau appears to be independent of confining field.

In this stage of the discharge, intense microwave generation, in the frequency range 10 000–70 000 Mc, has been observed. To date, detailed measurements have been restricted to the 35 000 ±2000 Mc range. The power levels of the received noise are of the order of 0.1 watt. The microwave generation generally occurs during the time of x-ray emission but may also occur considerably earlier, when the mean electron density first approaches the value (1.5×10^{13} cm^{-3}) at which a 35 000 Mc beam is no longer transmitted unimpeded by the plasma because of plasma resonance. Under certain conditions no microwave generation is observed during x-ray emission, possibly because the frequency of the generation has shifted entirely out of the response band of the receiver.

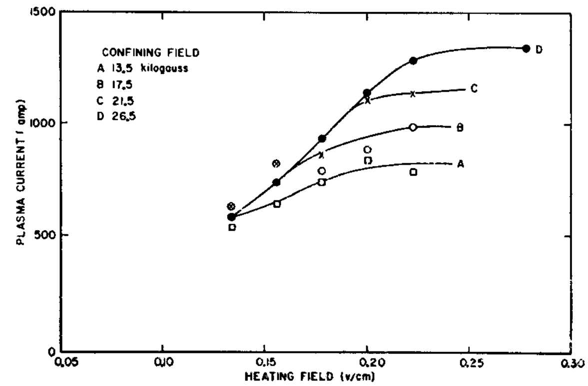

FIG. 4. Plasma current at the start of x-ray emission as a function of heating field, for several confining fields. Pressure: 1.5×10^{-3} mm-Hg.

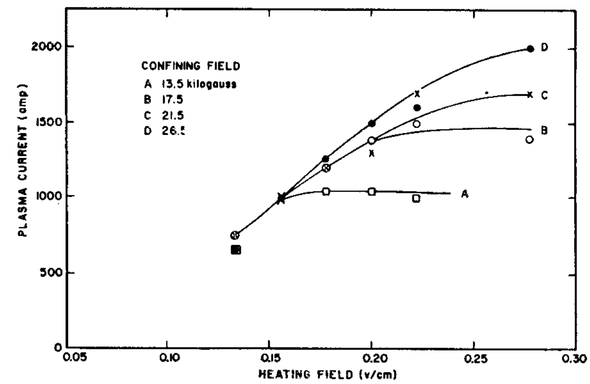

FIG. 5. Plasma current at the end of x-ray emission as a function of heating field, for several confining fields. Pressure: 1.5×10^{-3} mm-Hg.

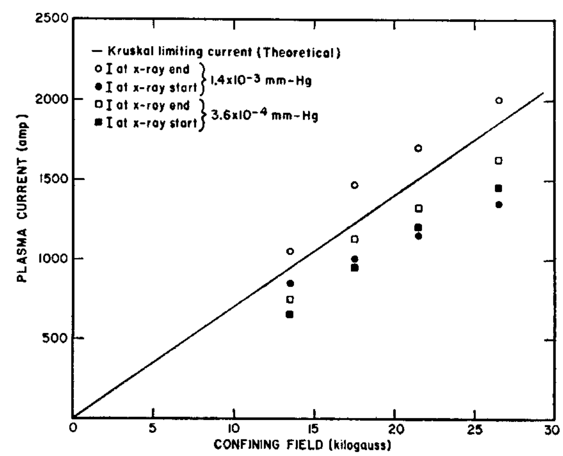

FIG. 6. Plasma currents at the start and end of x-ray emission as a function of confining field, for two pressures. High heating field.

In Fig. 6, plasma currents corresponding to the beginning and end of x-ray emission (Mode B), taken from the flat regions of the preceding figures, are plotted against confining field for two pressures. A family of curves through the origin of coordinates is obtained; some unexplained pressure dependence is observed only for the currents at the end of x-ray emission. The magnitudes of the currents shown at the end of x-ray emission (neglecting pressure) are in good agreement with the magnitudes of the Kruskal limiting currents calculated[5] for an assumed mean aperture of 7 cm^2, as shown. From these data, it appears that there is a relationship between the x-ray pattern and the Kruskal instability. Electrons are not expected to be confined and accelerated to sufficiently high energies to produce observable x-rays during the time the Kruskal instability dominates the discharge; the existing runaway electrons probably are not confined after the onset of the instability. Thus x-ray emission is not expected for the duration of the instability, in agreement with the experimental observations.

There are, however, several significant arguments against a causal relationship between a Kruskal instability and the x-ray emission pattern. At the low heating fields, the currents observed at the beginning and end of x-ray emission are far below those predicted, from the theory,[5] for this instability to develop. In fact, the absence of any confining field dependence in the observed currents is a strong refutation of the existence of any hydromagnetic instability. The absence of a relationship between the Kruskal instability and the x-ray pattern is less clear at high heating fields. If one assumes that the instability causes the start of x-ray emission, then it is difficult to explain the long duration of emission (50–200 μsec). If the Kruskal instability ended the x-ray emission, a pronounced increase in the intensity of the emitted radiation would be expected at the end of the emission period, since all the remaining runaway electrons would lose confinement at that time. However, the x-ray intensity shows no such peak, as shown in Fig. 7. (These data are not corrected for the transmission through the absorbers used.) This time distribution implies that all the runaway electrons are removed from the discharge before the Kruskal limiting current is attained; perhaps this is a necessary condition for reaching the Kruskal limit. The microwave generation pattern occurs at both the high and low heating fields and suggests that the same type of process perhaps occurs in both cases.

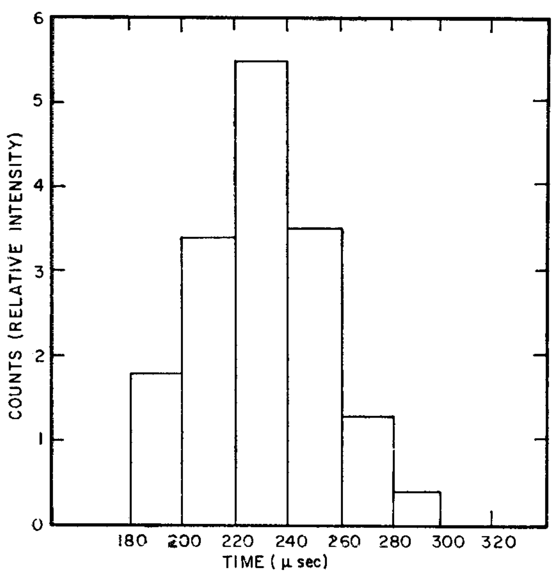

FIG. 7. Time distribution of x-ray intensity. Heating field: 0.12 v/cm. Confining field: 26.5 kilogauss. Pressure: 4×10^{-4} mm-Hg.

IV. CROWBAR DISCHARGE MEASUREMENTS

Significant information about the relation of runaway electrons to plasma characteristics may be obtained by the abrupt removal (crowbar) of the heating field during the discharge. In particular, both fast heating (constant voltage) and slow heating (constant current) cases have been examined using this technique. In many respects the results are similar.

Typical x-ray, voltage, and current patterns obtained when the voltage is crowbarred just at the beginning of x-ray emission are compared with normal patterns in Fig. 8; the operating conditions are high constant-voltage heating field (0.28 v/cm), high confining field (26.5 kilogauss), and a pressure of 1×10^{-3} mm-Hg. In the normal case, the current rises smoothly to the Kruskal limiting value; the voltage is essentially constant. The burst of x-rays begins at about 60 μsec after the heating field is first applied and terminates when the current reaches the Kruskal limiting value. In the crowbarred case, the current rises normally until the time of crowbar (60 μsec), and then decays slowly to a low residual value below 500 amp. The measured voltage is normal until the time of crowbar; the slow decay thereafter is the $L\,di/dt$ voltage produced by the current decay. The crowbarred x-ray pattern shows the beginning of x-ray emission (again at 60 μsec); here emission continues for several milliseconds. If the heating field is crowbarred after the current has reached the Kruskal limiting value, the current decays rapidly to zero; no later x-rays are

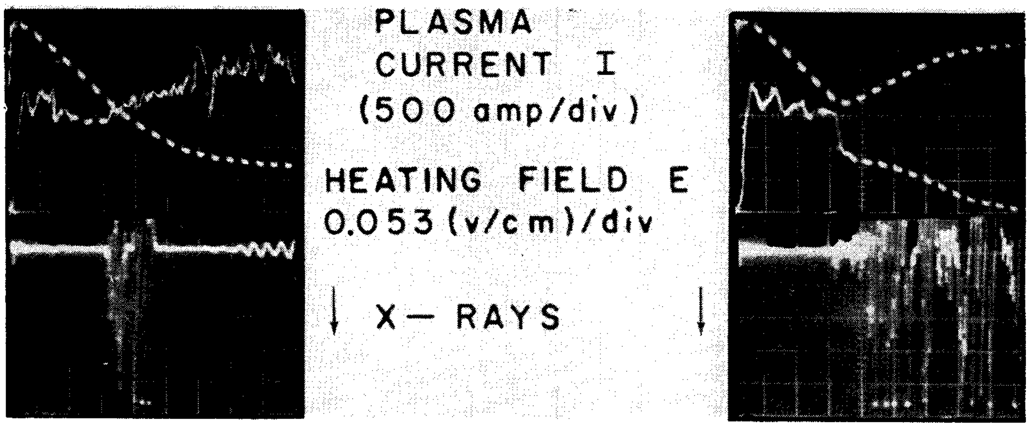

FIG. 8. Oscilloscope traces of plasma current, heating field, and x-rays, for the normal and crowbarred cases. Sweep speed: 20 μsec/div. Confining field: 26.5 kilogauss. Pressure: 1×10^{-3} mm-Hg.

emitted. In general, the later the crowbar time during the initial x-ray emission period, the lower the total x-ray intensity afterwards; the microwave generation ceases at approximately the time of crowbar.

It is apparent that many more x-rays were emitted after the heating field was crowbarred than were emitted *in toto* in the normal case. Using low counting rates and fast oscilloscope sweep speeds, a comparison was made of the number of x-rays emitted during the entire emission time of a normal pulse, and the number emitted during the time interval 80 to 530 μsec after crowbar; the heating field was crowbarred 60 μsec after it was applied. The ratios were obtained using the following absorbers: 0.3 cm Pb, 0.05 cm Cd, and 0.075 cm W. The end of the counting period in the crowbar case was chosen so that the time-integrated heating field available from the time of crowbar to the end of the counting period was the same as that which is available, in the normal case, from 60 μsec to the end of the emission period. This is verified to some degree since the maximum energies observed were about 200 kev in both cases. The number and energy distribution of the runaway electrons must have been the same at the time of crowbar in the two cases. Further, an electron at thermal energy at 60 μsec after the heating field was first applied could be accelerated to a maximum energy of only 45 kev by the heating field available after that time, in either case, and these would not be transmitted through the absorbers used.[6] Thus the difference in numbers of x-rays in the two cases can be due only to a difference in the subsequent behavior of the runaway electrons originally present at 60 μsec.

The ratio of total counts in the normal case to the number counted in the 450 μsec interval in the crowbar case was 0.2, with an estimated error of a factor of 2. This ratio was the same with each absorber.

From these data it seems clear that more x-rays are produced in the crowbarred discharge than in the normal discharge. This implies that, in the normal case, more runaway electrons were lost from the discharge without producing detectable x-rays than in the crowbar case. This would be so if, in the normal case, most of the electrons struck the limiter shortly after the beginning of emission, at which time they would have lower energies than in the crowbarred case and would be detected less efficiently. An alternative explanation, for the normal case, is that runaway electrons are reabsorbed into the plasma in nonradiative interactions; more striking evidence that this phenomenon can occur will be presented in a later section. At present the observations are not sufficient to substantiate either of these two possibilities. However, the mere fact that runaway electrons strike the limiter in abundance after crowbar indicates that even in this situation cooperative phenomena are taking particles to the wall.

V. CURRENT STEPS

Detailed observations of the residual current after crowbar and associated phenomena have been made. Figure 9 shows the behavior of the current, voltage, x-rays, electron density, and He I 4921 A light before and after the (constant-current) heating field is removed. The plasma current is seen to decay to a low constant value and to further decay abruptly at about 8 msec. The current is actually constant between steps; the apparent slope seen in

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[6] G. White, National Bureau of Standards, Rept. No. 1003 (1952) (unpublished).

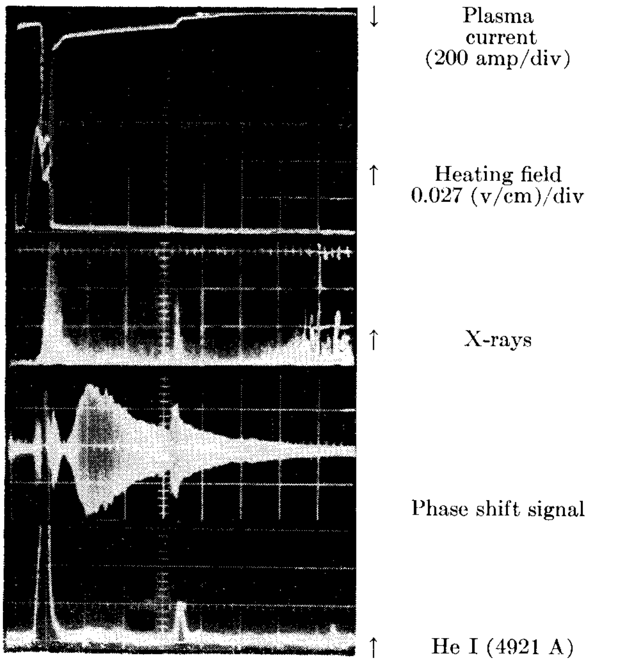

FIG. 9. Decay of residual current after crowbar, showing step phenomenon. Sweep speed: 2 msec/div. Confining field: 27 kilogauss. Pressure: 5×10^{-4} mm-Hg. Constant-current operation. Electron density is derived from the microwave phase-shift signal; [C. B. Wharton, Bull. Am. Phys. Soc. Ser. II, **3**, 86 (1958); UCRL Rept. No. 4836; R. F. Whitmer, Phys. Rev. **104**, 572 (1956)]; at the step the increase in phase-shift signal corresponds (nonlinearly) to an increase in density.

the figure is instrumental. Patterns vary from one to several steps per pulse; for a given set of operating conditions the general behavior is reproducible, although the exact time of the steps may not be. X-rays are emitted prior to crowbar; a pronounced peak coincides with the current step. Some x-rays are emitted continuously, although the rate is low. The electron density shows a steady decrease after crowbar; at the current step, the density increases by almost a factor of two and subsequently decreases again. A peak appears in the He I 4921 A light at the time of the current step.

Another pattern of residual current decay after crowbar has also been observed. Here, each current decrease consists of a rapid succession of three or four small steps; the sum of these is about equal to the single step in the previous case. Each of the small steps is accompanied by much more intense x-radiation than accompanied the large step; at the small steps there is no evidence for an electron density increase or excitation of neutral helium. Usually, only one kind of step occurs for a given operating condition depending on the duration of the discharge prior to crowbar. For short discharge durations, less than 0.5 msec, the single step pattern illustrated in Fig. 9 occurs; for longer times the multiple step pattern results.

There was some question as to whether this residual current could be attributed entirely to a circulating beam of runaway electrons. Unfortunately, because of the low-energy cutoff of the x-ray detector, the number of low-energy runaway electrons (below, say 50 kev) is unknown; and therefore one cannot obtain an upper limit to the circulating current which would be consistent with the observed x-ray flux. However, a very approximate lower limit can be obtained in the following manner. The x-rays emitted at 90° to the target during a current step were counted on a fast oscilloscope sweep. This was done when the second step pattern (multiple small steps with intense x-ray emission and no density increase) was present; the magnitude of the small step selected was 4 amp. The detector described previously was used. In addition, 3.8 cm Pb was used as absorber to decrease the counting rate until individual pulses were resolved; only x-rays above 400 kev, therefore, were observed. These were all assumed to be produced by 1.4 Mev electrons. This is a reasonable assumption in computing a lower limit to the current consistant with the observed x-ray flux, since any electrons with less energy than 1 Mev would yield fewer x-rays but would contribute almost as much to the circulating current. Furthermore, few electrons above 1.4 Mev can exist because no x-rays above 1 Mev were observed. The bremsstrahlung yield was computed using the data of Miller, Motz, and Cialella,[7] who measured the x-ray spectrum emitted at 90° from a tungsten target by 0.5 ma of 1.4 Mev electrons. These data were corrected for the difference in absorbers used in the two experiments; this correction was rather inaccurate because a large thickness of absorber was used in this experiment and because only narrow-beam x-ray absorption coefficients[6] were used. The corrected spectrum was integrated over energy to obtain the number of photons passing through the Pb absorber per electron striking the limiter. Finally, after correcting for solid angle and detector efficiency (70%)[8] we obtained, as a lower limit to the runaway electron current necessary to produce the observed average number (23) of x-rays during a step, the figure of 0.2 amp, as compared with the observed step current of 4 amp. Since the measurement was limited to x-rays above 400 kev, this very approxi-

[7] Miller, Motz, and Cialella, Phys. Rev. **96**, 1344 (1954).
[8] J. M. Berger and J. Doggett, Rev. Sci. Instr. **27**, 269 (1956).

mate lower limit is entirely consistent with the picture that the current steps after crowbar are caused by the sudden termination of confinement of a group of runaway electrons; at least in the case of the second step pattern, most of these strike the limiter and produce x-rays.

Both kinds of current steps give evidence for cooperative phenomena. In the case of the multiple steps, a group of runaway electrons apparently loses confinement and is abruptly led out of the discharge to the limiter. In the case of the single step, where reionization apparently occurs, it is possible that a cooperative process decelerates the runaway electrons, and they are abruptly reabsorbed into the main body of the plasma. Their energy raises the temperature of the plasma electrons and causes ionization and excitation. Only a few runaway electrons strike the limiter in this case. Although this mechanism is not an expected one, it would be difficult to account for the density and light increase at the time of the step in any other manner; ionization of neutral gas by the runaway electrons may account in part for the slow decay of electron density after crowbar, but it cannot account for an abrupt increase in density.

VI. CONCLUSIONS

It is obvious that much of the data cannot be explained on the basis of presently understood single particle models or macroscopic plasma physics, and that these data present further evidence for the existence of unexplained collective processes previously referred to as cooperative phenomena. It is possible that many of the inconsistencies observed during ohmic heating, referred to in the accompanying paper,[1] may be a result of these cooperative phenomena.

Two major conclusions may be drawn from this work. First, runaway electrons indicate the existence of instabilities at currents well below the Kruskal limiting current. Second, there is evidence that the runaway electrons themselves may affect the development of the discharge. In particular, there have been two indications that energy, at first given to the runaway electrons, can later be reabsorbed into the plasma. It is possible that in addition to the transfer of energy to the plasma electrons, as shown by the increase of ionization and excitation at the current steps, energy may also be transferred to the ions, perhaps causing anomalously fast ion heating.[3] The observed intense microwave generation may have significance in the general field of radio astronomy in that it may help clarify the mechanism producing microwave radiation from the galaxy.

ACKNOWLEDGMENTS

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