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Local Ion Direction of Motion and Electron Flow in a Magnetically Insulated Diode

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LPS 314

March 1983

CORNELL UNIVERSITY

ITHACA, NEW YORK

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Ion motion in a magnetically insulated diode was studied locally and simultaneously with the observation of the local electron flux to the anode. Sudden, brief ion deflections accompanied by intense electron bursts to the anode, were observed, evidently resulting from transverse electric fields in the diode gap. Slowly rising deflections of two classes were also found. The data suggest that they were caused by electric fields resulting from a changing shape of the anode plasma surface due to a local increase in the plasma expansion velocity for one class and due to plasma depletion for the other. The shapes of the perturbations in the potential surfaces for both classes were deduced. The relation of each perturbation to the change in the electron flux to the anode may be explained qualitatively by considering the motion of a single particle. The size of the potential perturbations was shown to be a few centimeters and the magnitude of the transverse electric fields was inferred to be up to 0.3 of the diode accelerating field.

I. Introduction

Intense ion beams generated by pulsed magnetically insulated diodes are potentially useful for Inertial Confinement Fusion,[1] and for plasma confinement, stabilization, and heating for magnetic confinement fusion.[2] An important requirement for such applications is a sufficiently small divergence of the ion beam.[2-3] The ion beam divergence is believed to be determined by temporal and spatial changes of either the electric or the magnetic fields due to various factors. These factors include anode plasma nonuniformities,[4-6] electron-sheath instability,[7] nonuniformities near the cathode extraction region, and self-space-charge fields outside the diode. The relative contribution of each factor has not been investigated as yet.

Ion beam divergence has been measured in several studies[8,6] by extracting ion beamlets through tiny apertures, and observing the spots they produce on a target. However, such measurements are generally ambiguous since at each instant of time ions from different regions of the diode may pass through the apertures. Also, it was difficult to study the effect of each of the possible sources of the ion beam divergence from such measurements. The mechanisms responsible for electron convection to the anode in a magnetically insulated diode are also not understood as yet. This convection not only directly affects the electron residence time, and thus the ion generation efficiency,[9-10] but also may cause spatial and temporal variation in the ion beam.

In this study, a portion of the extracted ion beam was allowed to pass through a relatively large aperture, 14 mm in diameter, and to hit a scintillator sheet. This enabled us to observe most of the ions emitted from a selected area of the anode throughout the diode pulse. Thus, we could obtain the characteristics of the changes in the ion direction of motion, such as time scale, magnitude, the direction of the changes, as well as the relationship of such changes to variations in the ion current density. In addition, we monitored the relative electron flux to the anode to the same anode area which was viewed by the ion detector, as described elsewhere.[11] The relation between changes in the ion direction of motion and in the electron flux to the anode implied that the ion deflections occurred inside the diode. The measurements were also used to infer the size of the region of the diode involved in the perturbation, and to deduce that the observed ion deflections could not result from magnetic fields, but rather had to be due to electric fields. A detailed analysis of the characteristics of the observed ion deflections, which will be described specifically for each class of the findings, allowed the elimination of ambiguities in previous measurements of the ion beam divergence.[6] The results allowed to deduce the presence of perturbations in the equipotential surfaces in the diode gap. In one of the three data classes described in this paper the bursts of electrons to the anode appeared to be the cause of the perturbation and in the other two classes it is highly likely that the equipotential surfaces followed a local perturbation in the shape of the anode plasma. Other suggestions which could in principle explain the findings were also considered but were found to be inconsistent with the data, as will be discussed for each of the data classes.

We performed our experiments using the LONGSHOT diode.[12] To summarize the results, we observed sudden ion deflections, which lasted 10-30 ns, and slow ion deflections which grew over 100 ns or more.[13] The short deflections will be described in Sec. III. It was concluded that they result from transverse electric fields associated with local electron bursts to the anode. Since the electron bursts occurred with and without anode plasma[11] it was deduced that these transverse fields resulted from processes in the cathode plasma or in the electron sheath. The data implied that the local perturbations in the potential surfaces were "valley-shaped", i.e., the surfaces are closer to the anode in the perturbation center. The size of the perturbation along the azimuthal direction was found to be 10-30 mm.

The slow ion deflections included two major classes. The defections of the first class, described in Sec. IV A and B, started with an increase in the ion current density. They were evidently caused by a "hill-shaped" potential perturbation and were not accompanied by a change in the electron flux to the anode. It is suggested that these perturbations resulted from a local increase in the anode-plasma expansion rate. The slow deflections of the second class occurred together with an increase in the electron flux to the anode (Sec. IV C and D) and appeared to be associated with a valley-shaped potential perturbation. This could result from a local plasma depletion. The relation of both slow deflections to the increase in the electron flux to the anode is discussed in Sec. V. An explanation to this relation, based on considerations of a single particle motion, is offered. The increase of the electron flux was found to occur within 1-2 cm of the potential perturbations of class B, as will be described in Sec. VI. The magnitude of the transverse electric fields, averaged across the diode gap, was found to be 0.1-0.25 of the diode applied field. Additional results which support the suggested role of the anode-plasma shape in determining the ion direction of motion are presented in Sec. VII, and concluding remarks are given in Sec. VIII.

II. Measurements

The LONGSHOT[12] magnetically insulated diode used for the present study has an annular accelerating gap and a radial insulating magnetic field B, as shown in Fig. 1(a). The anode is made of lucite, drilled with 1 mm diameter holes 5 mm apart. The insulating magnetic field was $\gtrsim$3 kG[14] which is more than twice the critical field for magnetic insulation.[15-16] The pulse lasts about 700 ns with typical voltage and current waveforms shown in Fig. 1(b).

A diagram of the method by which the ion beam divergence measurements were made is shown in Figs. 1(a) and 2(a). A portion of the ion beam was selected by a circular aperture, 1.2-1.4 cm in diameter, placed 4.6 cm from the anode and centered on the middle of the anode annulus. Then, this portion of the ion beam passed through a 1 mm wide and 40 mm long slot located 2.4 cm from the aperture, with its long dimension parallel to the azimuthal direction of the anode. After traveling an additional distance of ~3 cm the ions impinged on a pilot B scintillator sheet which was photographed by a fast streak camera. Thus, ion deflections in the azimuthal direction could be observed. The writing speed of the steak camera was calibrated with 100 MHz light pulses of a mode locked laser. The starting time of the camera sweep with respect to its trigger was determined by photographing a train of light pulses in which the light of each tenth pulse was deflected by an optical cell into a photodiode. The position on the film of the scintillator region hit by the ions at t = 0 was determined by two static photographs. One was made on a separate piece of film, giving the scintillator location and the camera magnification. In the other, an edge of the scintillator was photographed to give a reference spot on the same piece of film as in the dynamic photograph. An example of a streak photograph is shown in Fig. 2(b). The time of ion flight to the scintillator was calculated using the instantaneous diode voltage. (The ions could be assumed to be protons since >80% of them were previously determined to be protons,[13] and also since the pilot B scintillator is a few times more sensitive to protons than to carbon ions.[6]) Our estimates and also the experimental observations yield an error smaller than ±15 ns in the time determination along the streak. Most of this uncertainty was contributed by the divergence of the ions in the radial direction (which coincided with time direction on the film).

By changing the aperture-scintillator geometry the light from the scintillator increased with an increase in the ion current density on the scintillator. It was inferred that the scintillator response was close to linear under the conditions used for the present experiments.

Observation of small ion beamlets obtained using tiny holes yields relatively accurate changes in the ion direction of motion. Therefore, we performed such experiments in order to reexamine the occurrence of the large changes in the ion direction of motion observed by the measurements described above. Ion beamlets, selected by 1-3 mm diameter apertures, hit the scintillator screen. These measurements showed slow and fast changes of up to 19° in the ion direction of motion, in agreement with the changes inferred from our large-aperture measurements to be presented here. In these measurements the azimuthal shift of the ions, due to their traversing a nonzero net radial magnetic flux, was also observed. This shift, a few millimeters at ~10 cm distance from the anode, was taken into account in determining the anode area from which the ions which passed through the large aperture were emitted.

A local relative measurement of the electron flux to the anode was made by monitoring the bremsstrahlung emission from the anode using a collimated scintillator-photomultiplier x-ray detector, as shown in Fig. 1(a). The small sensitivity of the recorded bremsstrahlung signal to the incidence angles of the electrons was discussed in Ref. 11. The signal depends on the time-dependent diode-voltage but this dependence did not affect the conclusions to be drawn here, as will be shown. Generally, we used two x-ray detectors which looked near the anode area viewed by the ion beam system. The areas viewed by the detectors were radially centered on the anode annulus. Their sizes and the degree of their overlap were varied in the experiments.

III. Short Ion Deflections

A. Results and Implications

The streak photographs revealed increases in the ion beam divergence, which lasted for 10-20 ns, in roughly one-third of the shots. An example of such an ion deflection, called here a "short deflection", is shown in Fig. 3(a). A short increase in the streak width in both the direction of the electron drift in the diode [called here "the +θ direction" - see Fig. 2] and opposite to it ($-\theta$ direction) is observed. The electron flux signal obtained in the same shot is given in Fig. 3(b). The size of the anode area viewed by the bremsstrahlung detector was 42 mm in the azimuthal and 12 mm in the radial directions. Two short electron bursts are observed, the first of which coincides (within the time-determination accuracy of ±15 ns) with the short ion deflection. In our shot series we observed 37 short ion deflections, more than 80% of which were found to coincide with short electron bursts to the anode. About one-third of the electron bursts were found to be simultaneous with short ion deflections.

The short ion deflections were found to occur in a region close to that of the electron bursts to within 1-2 cm, as will be discussed in Sec. III.B. The strong temporal and spatial correlation between the short ion deflections and the electron bursts to the anode indicate that the ion deflections originate in the diode. This conclusion is supported by additional results (see below in Sec. III.B) which showed that short ion deflections in only one of the azimuthal directions could also occur. Such deflections cannot result from self-field expansion of the ion beam outside the diode because such an expansion would widen the ion beam in both directions.

In principle, an increase in the width of the ion beam image on the streak photograph could result from an expansion of the anode region from which ions were emitted, without an increase in the angle of the ion trajectory with respect to the normal to the anode (this angle will be denoted here by α). However, tracing of ion trajectories showed that the observed width increase could not occur without a substantial increase in the angle α as will now be described. Following the conclusion that the change in the streak width was caused by effects in the diode, we could use ray tracing from the scintillator to the anode, as shown in Fig. 4 for the photograph in Fig. 3(a). The lines $\overline{AB}$ and $\overline{CD}$ indicate the scintillator region hit by ions during and before the short deflection, respectively. The maximum possible angle α_1 before the widening was determined by assuming that the ions reaching $\overline{CD}$ originated at a single point on the anode. Since the value of α_1 is determined by the position chosen for this point on the anode, we chose the position E which gave the largest value for α_1, i.e., the angle which $\overline{DE}$ makes with the normal to the anode ~8° (the dashed lines $\overline{CE}$ and $\overline{DE}$ indicate the illumination of the region $\overline{CD}$ by ions from E). The minimum angle α_2 during the deflection was determined by assuming ion emission over the entire anode. This angle is determined by the line $\overline{BG}$ giving 15° with respect to the normal. Thus, we concluded that the trajectories of ions which passed through the aperture during the short deflection were deflected by at least 15° - 8° = 7°.

It could still be argued that the increase in α of the ions passing through the aperture does not necessarily imply an increase in the angle α of the ions emitted from the anode. For such an argument one assumes that α is large even before the deflection but the observed α at this stage is small because it is limited by the aperture geometry. Thus, an apparent increase in α can result from the motion of a small ion-emitting source over the anode because such a motion geometrically allows ions with different angles to pass through the aperture at different times. This possibility is precluded here since, for instance for the photograph in Fig. 3(a), the streak width $\overline{CD}$ prior to the short width increase was not limited by the ion aperture. Thus, the maximum of the angle α prior to the streak width increase, i.e. α_1, was not geometrically limited by the aperture (see line $\overline{DE}$ in Fig. 4), i.e., it was indeed small. Also, if ions were deflected by a large angle α not only during the short increases in the streak widths, one would expect that we would have observed in many cases large angles (as large as the ones associated with the short deflections) prior to or after the short streak width increases. However, the ion deflections were almost always much larger during that brief period. In summary, we conclude that during the short streak width increases the angles α of the trajectories of ions which passed through the aperture substantially increased, and that this increase did not appear due to temporal or spatial changes in the ion emission site at the anode, but rather it was was caused by an increase in the ion transverse velocities.

The observed ion deflections with respect to the diode axis varied in different pulses between a few degrees and 20°. These changes in the ion direction of motion could not result from changes in the local magnetic field in the diode gap which accompany the electron bursts. The amplitude of these changes were estimated[11] to be about 200 G. Such a change in the magnetic field in the diode gap can alter the direction of a proton accelerated there by about 0.5°. This leads to the conclusion that transverse electric fields are formed in the diode gap in the vicinity of the electron bursts. The fact that ions are deflected in both azimuthal directions means that transverse electric fields in both directions are produced. The average magnitude of the transverse fields across the gap must be as high as about 1/3 of the diode accelerating field in order to account for the largest observed ion deflections.

B. Shape and Size of the Potential Perturbation

Tracing of the ion trajectories was used to determine the location of the transverse electric fields, as also shown in Fig. 4. Ions reaching the scintillator points A and B could be emitted from any point on the anode within the region $\overline{HI}$ and $\overline{JK}$, respectively. This is indicated by the solid lines $\overline{HA}$ and $\overline{IA}$ and the dotted lines $\overline{KB}$ and $\overline{JB}$, respectively. A reasonable shape of the equipotential surfaces in the diode gap during the short ion deflection, which allows for such ion deflections, is that depicted by the solid line ℓ of Fig. 4. The transverse electric fields due to such a perturbation in the equipotentials, called here a valley-shaped perturbation, deflect ions from the region HI in the $+\theta$ direction and ions from the region JK in the $-\theta$ direction. Such a perturbation in the equipotential surfaces is probably due to a local increase in the electron density in the gap, which reduces the potential near the cathode. Such an increase in the electron density would also tend to increase the gap ion-density. This is consistent with the observed sharp peaks in the ion current density simultaneously with the electron bursts.[11]

Local changes in the electric fields in the diode can, in principle originate with changes in the anode or the cathode plasmas, or with changes in the electron sheath structure. However, the electron bursts also occurred in the absence of anode plasma and ions in the diode gap, suggesting that the electron bursts were initiated by processes in the cathode plasma.[11] Since the short-duration ion deflections were observed to coincide with the electron bursts we conclude that the inferred transverse fields accompany the formation of these bursts, i.e., their causes are not associated with anode-plasma behavior. However, the presence of ions in the diode gap may affect the magnitude of these transverse fields.

Experiments were carried out to study the localization of the transverse electric fields. Let us assume that the center of the perturbation in the potential occurs a few millimeters from the center O of the viewed anode area, say at the point O_1, which is located in the $-\theta$ direction with respect to the point O [see Fig. 5(a)]. Then, if this perturbation stretches over a distance comparable to the ion-aperture diameter, ions originating to the left of O_1 (solid line) will be deflected in the $-\theta$ direction and will miss the ion aperture while those originating to the right of O_1 (dashed line) will be deflected in the $+\theta$ direction and may still pass through the aperture. In this case a short ion deflection only in the $+\theta$ direction will be observed. Thus, in order to study the size of the potential perturbation, we performed experiments in which the deviation of the perturbation center from the point O could be indicated. Such an indication might be given by the deviation of the corresponding electron burst from this point. In order to determine the electron burst location, two electron flux detectors, (X_1 and X_2) were used, each viewing a circular anode area ($\overline{LM}$ and $\overline{NP}$, respectively) 15 mm in diameter centered 10 mm on opposite sides of the point O, see Fig. 5(a). Thus, an electron burst seen by one detector which did not occur very close to O will not appear on the other. In this 21-shot series we observed 11 short ion deflections occurring only in one direction. Ten of them coincided with electron bursts observed on only one detector. When the burst occurred in the $-\theta$ side of the point O (observed only by X_2) it corresponded to an ion deflection in the $+\theta$ direction and vice versa, as expected if the perturbation size is comparable to the ion-aperture diameter. An example of such a short deflection is presented in Fig. 5(b), where ions are deflected only in the $+\theta$ direction. (Other details of this photograph will be discussed later.) From this class of data we were able to conclude that the width of the perturbations in the potential surfaces in the azimuthal direction varied between 10 to 30 mm.

IV. Slow Ion Deflections

In addition to the short duration deflections, slowly growing ion deflections were also observed. These deflections could be divided into two distinctly different classes which are discussed in this section.

A. Class A Deflections

We will describe the features of the first group by referring to the streak photograph shown in Fig. 6(a). There it can be seen that a sudden (~10 ns) increase in the light intensity, which means a sudden increase in the ion current density J_i, is observed. No change in the ion direction of motion appears with this increase. However, at this instant, a deflection of ions (in this case in the $+\theta$ direction) starts growing, and continues to grow for about 250 ns. Generally, the ion deflections grew for more than 100 ns and in more than half of the cases the streak was broad up to the end of the streak.

The observed ion deflection shown in Fig. 6(a) could not result from self-space-charge fields outside the diode which could accompany an increase in ion current density. This is because in this case the ion deflection would occur simultaneously with that increase. Also space-charge fields would deflect the ions in both azimuthal directions, rather than in the one direction seen in Fig. 6(a). We note that the possibility of an ion source moving over the anode, and thus causing an apparent ion deflection, is also precluded here due to similar arguments used in Sec. III for the short ion deflections. Thus, we conclude that a change in the ion direction of motion indeed occurred and that this change originated at the diode. In the example in Fig. 6(a), the deflection of the streak implies that the final change in the ion direction of motion is $\lesssim 12°$ (estimating the minimum possible change in angle, as described in Sec. III.A, gives 5°).

The size of the anode area over which the sudden increase in J_i occurred was obtained from experiments where ion beamlets, passing through several small adjacent apertures, were observed. It was found to vary between about 5 and 30 mm in the azimuthal direction.

B. The Explanation for the Class A Deflections and its Experimental Support

We suggest the following explantion to the deflections of class A. The ion current density is locally limited by the rate of ion-supply from the anode plasma (the electric field on the anode plasma is >0). Therefore, if this rate increases locally, considerable increase in J_i is observed. Such an increase, although locally modifies the electric potential in the diode gap, does not result in sufficiently large transverse electric fields to cause a detectable ion deflection, as will now be estimated. For this estimate we used the potential profile in the diode gap, given by a one-dimensional equilibrium[16] in a magnetically insulated diode, for a space-charge-limited ion emission from the anode. By the same treatment we obtained the potential distribution for zero ion emission. The difference between these two profiles gives an upper estimate for the potential variation caused by fluctuations in J_i. We assumed that these two distributions prevail in two regions separated by 1 cm. The lines joining the equipotentials gave transverse electric fields which could deflect the ion trajectory only by about ~2°, which is hardly noticeable in our measurements. This shows that an increase in the rate of the ion-supply from the anode plasma is not likely to cause a large ion deflection directly, as was observed in the experiment.

Since the rate of the ion supply from the plasma is determined by both the plasma temperature and density, a local increase in this rate implies a local increase in these quantities. It is reasonable to assume that this results in an increase in the local plasma expansion velocity. Consequently, the plasma gradually protrudes into the diode gap. The equipotential surfaces would follow the shape of the anode plasma surface, thus will be distorted to form a hill-shaped perturbation, as depicted in Fig. 6(b). The gradual growth of this perturbation explains the gradual increase in the ion transverse velocities.

The explanation given above is supported by the following experimental findings. We will first discuss a support to the assumption that the increase in J_i is not caused by instabilities of the electron sheath (which could lead to an enhancement of the electric field on the anode plasma and thus to a stronger ion emission), but rather it is due to a local change in the anode plasma. In many shots the increase in J_i occurred over an anode region as small as a few millimeters which is smaller than the diameter of the ion aperture. In these cases it was seen that the region of increased J_i remained fixed to within a few millimeters for more than 100 ns, as shown in the example in Fig. 7. Such a situation is much more likely to happen if the increase in J_i results from an increase in the ion supply rate in a specific region of the anode plasma, rather than from a variation (not induced by changes in the boundary plasma) in the electron sheath structure, since the latter is expected to change on the electron motion time scale (of the order of a nanosecond).

The rise time of the ion deflection is large as compared to the electron motion time scale, while it is consistent with the time-scale of plasma-expansion here assumed. The anode plasma is known to have a temperature near 1 eV and about a 2 cm/μs expansion velocity.[17] A local increase of a few tens of percent in this velocity gives a period of ~100 ns for the anode plasma to protrude locally about 1 mm, or about 10% of the diode gap, into the diode gap.

The observed ion deflections of this class were found to support the formation of a hill-shaped potential perturbation as that drawn in Fig. 6(b). With such a perturbation one expects the following: If the perturbation center occurs at the center O of the anode area viewed by the ion detector, ions emitted from the two sides of the point O, thus being deflected in opposite azimuthal directions, will still pass through the aperture [see lines a and b in Fig. 6(b)]. Hence, the streak width will increase in both directions. However, such a widening will be small due to the following reason. If the size of the perturbation is comparable to the aperture size (14 mm) or less, the transverse electric fields a few millimeters from the perturbation center will be relatively small. Thus, the deflection angle of ions emitted from the vicinity of the point O, say from the points A and B which are located at 3 mm from O, will be relatively small (lines a and b). Ions with a larger deflection, emitted from a region farther from the point O, say from the point C which is located at 5 mm from O, will not be observed since they will not pass through the aperture [see line c in Fig. 6(b)]. From the measurement geometry it can be easily seen that when the perturbation is centered with respect to the aperture, only ion deflections of a few degrees can be observed. Consider now the case in which the perturbation center occurs at a point O_1 which is located a few millimeters from O (in the $+\theta$ direction, for instance), as shown in Fig. 6(c). Then ions passing near the edge D of the ion aperture [line a in Fig. 6(c)] will have a small deflection since they originate near the perturbation center. However, ions with large deflections (not originating close to the perturbation center) can pass through the aperture edge E [line b in Fig. 6(c)]. Therefore, the deflection of the streak will be as small as the previous case [the case in Fig. 6(b)] on its left side (side of the aperture edge D), but will be larger on the right side (side of E). In continuation to this, when the perturbation center occurs even farther from the aperture center than the case in Fig. 6(c), ions passing through both edges of the aperture will appear to be deflected, and in the same direction. Thus, in this case, the entire streak will be deflected in one direction and the observed ion deflection angle will be larger than in the two previous cases. Indeed, this analysis was confirmed by 14 cases out of the 18 observed deflections of this class. Examples of these three cases are given in Figs. 8(a)-8(c). Figure 8(a) shows a streak which widens in both directions. The corresponding change in the ion direction of motion is about 3°, corresponding to the diagram in Fig. 6(b). In Fig. 8(b), the left side of the streak photo-graph shows a change of 5° (in the $-\theta$ direction) in the ion direction of motion, while the right side indicates a deflection of 11°, in the same direction [corresponding to Fig. 6(c)]. In Fig. 8(c), the entire streak photograph bends in one direction and the ion deflection is 15°.

C. <u>Class B Deflections</u>

The characteristics of the slow class B deflections can be seen in the example shown in Fig. 9(a). Prior to the start of the slow deflection a relatively low ion current density is observed. The ion deflection grows in both azimuthal directions (unlike the class A deflections). During this growth, the light intensity in the middle part of the streak is low with respect to that in the sides, as seen in Fig. 9(a). This indicates a relatively low ion-current density in the central part of the observed anode area. The ion deflections grew, on the average, faster than those of class A. For the same final change in ion direction of motion the deflections grew in a few tens to 100 ns while those of group A grew in 100-200 ns. We observed 29 deflections of class B out of a series of 120 shots. We note that the characteristics of this class, shown in Fig. 9(a), were observed somewhat differently in different cases. However, in 75% of the observed cases the central part of the streak showed low ion current density during the deflection. A decrease in the ion current density a few tens of ns or more prior to the start of the ion deflection was observed in about half of the cases. The considerable broadening of the streak in both directions was also observed in about half of the cases. Another example of a slow class B deflection can be seen in the streak photograph presented in Fig. 5(b), where the deflection starts about 60 ns before the short deflection marked by the arrow. There, a decrease in J_i just prior or coincident with the start of the ion deflection, an ion deflection only in the $+\theta$ direction, and a low ion current density in the central part of the streak during the deflection period, are observed.

Such a broadening of the streak could not result from an expansion of the ion beam under its own space-charge fields outside the diode since such an expansion would not have produced an ion current density in the central part of the beam lower than that at the beam edges. Thus, it is concluded that the ion deflections originated in the diode. (This conclusion will be further supported by the correlation with the electron flux to the anode discussed in the next section.) Also, it will be further shown that the slow deflections of both classes were either not accompanied by changes in the electron flux to the anode or accompanied by changes with amplitudes smaller than the intense short electron bursts. Thus, similarly to the short duration ion deflections, the slow deflections of both class A and B must not have resulted from local changes in the magnetic field in the diode.

D. The Explanation of Class B Deflections and Its Support

This class of ion deflections can be reasonably explained by assuming that a local decrease in the ion supply rate from the plasma causes the observed local decrease in the ion current density. This shortage of ions would also cause a depletion of that portion of the anode plasma which would consequently retreat towards the anode electrode, causing a dip in the plasma surface. This leads to a valley-shaped perturbation in the potential surfaces, as depicted in Fig. 9(b). The resulting transverse electric fields deflect the ions in both azimuthal directions as shown by the solid lines of Fig. 9(b). Notice that the valley-shaped perturbation allows the observation of large ion deflections in both directions simultaneously, in contrast to the hill-shaped perturbation previously discussed [see Fig. 6(b)]. Also, in the case of the valley-shaped perturbations, ions deflected in both directions will simultaneously pass through the aperture even if the perturbation center is a few millimeters away from the center O of the anode area viewed by the ion detector as indicated by the dashed lines in Fig. 9(b) [in contrast to the hill-shaped perturbation shown in Fig. 6(c)]. The potential surfaces will remain disturbed as long as the plasma cannot replenish itself, consistent with the low ion current density observed throughout the deflection. The fact that a deflection in only one direction was sometimes observed could be due to a perturbation which was not symmetric azimuthally or to the possibility that ions deflected in the other direction missed the ion aperture. The rise time of the deflections is determined by the formation time of the dip in the anode plasma which, evidently, may be different from the time needed for the plasma to protrude into the diode (which we concluded to occur in class A deflections), as was observed. The perturbation is very unlikely to be caused by processes in the electron sheath because the time scale of both the decrease in the ion current density and of the ion deflection is much longer than the electron motion time scale. Also, if the valley-shaped perturbation were caused by a local accumulation of negative charge it should have led to an increase in J_i rather than to a decrease.

Using ray orbits for the ions through the ion aperture, the size of the perturbation along the azimuthal direction was found to be 2-4 centimeters. This result is consistent with many shots in which two identical ion apertures, separated by 5 cm in the azimuthal direction, were simultaneously used. In these shots, no correlation between deflections observed through the two apertures was found.

Finally, most of the observed slow ion deflections could be categorized into these two classes (A and B) of ion deflections. In about one-third of the streak photographs no large ion deflections were observed [the streaks looked similar to that of Fig. 2(b)]. These cases indicated a "quiescent" ion divergence of a few degrees.

A systematic difference between the number or the magnitude of ion deflections in each of the $+\theta$ or the $-\theta$ directions could imply that the relative magnitude of the transverse electric fields in these two directions is affected by the electron E x B flow. Statistically, no such difference was found, indicating that the transverse fields, averaged over many shots, are symmetric with respect to the plus and minus θ directions.

V. Relationship Between the Electron Flux to the Anode and the Slow Ion Deflections

Since the slow perturbations in the potential surfaces are believed to originate with changes in the shape of the anode plasma, and since the slow variations in the electron flux to the anode occur mostly in the presence of the anode plasma,[11] we examined the relations between these two phenomena.

Ion deflections of class A, either in the $+\theta$ or in the $-\theta$ directions, were not accompanied by increases in the local electron flux to the anode. This result was obtained in ~80% of the cases and is shown, for example, in Fig. 10, where the bremsstrahlung signal corresponding to the ion streak photograph of Fig. 8(c) is given. The bremsstrahlung signal decays during the portion of the pulse in which the ion deflections are growing significantly [up to 15° in the case shown in Fig. 8(c)]. While a considerable fraction of the bremsstrahlung signal decay was estimated to be due to the decrease of the diode voltage, we could clearly deduce that no increase in the electron flux occurred.

Ion deflections of class B were generally accompanied by an increase in the electron flux to the anode in cases where deflections in the $+\theta$ direction, or deflections in both the $+\theta$ and the $-\theta$ directions, were observed. The x-ray signal increased in $\gtrsim 75\%$ of such cases, while only 20% of the cases, in which only deflections in the $-\theta$ direction were observed, were accompanied by an increase in the x-ray signal. Figure 11 shows two examples of an increase in the x-ray signal with a $+\theta$ ion deflection of class B. In the streak shown in Fig. 11(a), a short ion deflection (indicated by the solid arrow) occurs after which the streak width increases, mostly in the $+\theta$ direction. Later there appears a distinct spot at the left side of the photograph (dashed arrow) which indicates an additional ion deflection in the $+\theta$ direction. The corresponding rise in the electron flux is shown in Fig. 11(b). A short peak in the x-ray signal (solid arrow) coincides with the short ion deflection. The x-ray signal then gradually rises until it rises sharply at the dashed arrow. This rise coincides with the start of the spot on the left side of the streak photograph (this spot is of the type of short deflections, although it seems to be of a relatively long duration--25 ns). In the streak shown in Fig. 11(c), a $+\theta$ deflection starts at the time indicated by the arrow. The rise in the x-signal [see Fig. 11(d)] starts at the same time (high short x peaks are then imposed on the long x-signal). The increase in the electron flux associated with the $+\theta$ deflections of class B almost always lasted over the entire deflection duration. We note, though, that it was difficult to quantify the relation between the time variation of the x-ray signal and of the ion deflection.

We try to understand these electron flux results by considering the motion of a single particle under the effect of a hill-shaped and a valley-shaped perturbation. An electron moving parallel to the anode towards a hill-shaped perturbation in the potential surfaces first encounters accelerating transverse electric forces F_t [see Fig. 6(b)], i.e., transverse fields which increase the electron velocity in the direction of the E x B electron drift. The electron acceleration due to such fields results in an increase in the magnetic force, thus perturbing the balance between the magnetic and the electric forces acting on the drifting electron. An increased magnetic force causes an electron deflection towards the cathode. The gain in velocity towards the cathode prevents the electron from moving towards the anode even when the electron passes through the perturbation center and reaches decelerating transverse electric fields which tend to deflect it back towards the anode. On the other hand, an electron which approaches a valley-shaped perturbation of the potential, will first be subjected to decelerating transverse electric forces [see Fig. 9(b)], leading to a reduction of the magnetic force and thus to an electron deflection towards the anode. This explains the rise of the electron flux to the anode, when class B ion deflections in the $+\theta$ direction (which means deflections caused by transverse fields in the $+\theta$ direction, i.e., fields which decelerate the electrons) are observed. When the decelerating fields of the valley-shaped perturbation, at the region viewed by the ion detector, are small (in this case the observed ion $+\theta$ deflections are small) electrons are less likely to reach the anode. They mainly encounter the accelerating transverse fields of the valley-shaped perturbation. This explains the absence of increase of the electron flux when class B deflections only in the $-\theta$ are observed.

VI. Localization of the Class B Potential Perturbation and the Electron Flux to the Anode

Electrons which gain velocity towards the anode, due to transverse electric fields, will not necessarily hit the anode at the location of the field perturbation because of their E x B drift parallel to the anode. Thus, having established the relationship between the direction of the transverse electric fields and the electron convection to the anode, we examined the localization of the increased electron flux and its average distance from the class B potential perturbations. Most of the increased electron convection to the anode in our experiments occur close to the decelerating transverse fields, since only 25% of the observed $+\theta$ deflections were not found to be accompanied by increases in the electron flux measured by a detector which looked in the vicinity of the anode area viewed by the ion detector. In order to further check this conclusion, additional experiments were carried out where two x-ray collimators, X_1 and X_2, were aimed at the anode, each one viewing a 15 mm-diameter region of the anode on azimuthally opposite sides of the region viewed by the ion detector [see Fig. 5(a)]. Ions deflected in the $+\theta$ direction, which pass through the aperture, should originate from the anode region right to the point O, as shown by tracing ion orbits [see Fig. 9(b)]. This means that in this region electron-decelerating transverse electric fields occur. If the associated increase in the electron flux occurs over an area which is close to this area, then this increase should be observed by the X_2 collimator which looks to the right of the point O.

In this 21-shot series nine cases of class B deflections in the $+\theta$ direction were observed. In five cases an increase in the electron flux was observed only by the collimator X_2, in one case by both X_1 and X_2, in two cases only by X_1, and in one case no increase was detected. Also, in both cases where the signal increase was detected only by X_1, the increase was relatively small, lower than the average increase of the cases of only X_2.

These results further support the conclusion that the increase in the electron flux occurs within 1 or 2 centimeters of the region of the decelerating transverse electric fields. It seems that the increase is relatively small when it occurs farther from the field perturbation (observed only by X_1). This could be due to the fact that electrons hit the anode over a larger area.

Since the observed slow changes in the ion direction of motion were between a few to 15°, the transverse electric field averaged over the diode gap is inferred to be 0.1-0.25 of the diode axial field. Such fields can be expected to perturb the electron trajectories significantly. The portion of the anode hit by the electrons will be determined at least in part by the electron distance from the anode. The electrons in the LONGSHOT diode are believed to be E x B drifting roughly within 2 mm of the anode[10] (as indicated by the ion current density being about 30 times the value predicted from space-charge limit, using the 1 cm physical K-A gap). Therefore it seems reasonable that with such considerable transverse electric fields the electron flux increased within 1-2 cm of the perturbations transverse fields.

From these and from other experiments we deduced that about one-half of the slow increases in the electron flux, observed by a detector which looked to the right of the point O, were associated with slow class B ion deflections in the +θ direction. On the other hand, only 25% of the increases observed by a detector which looked to the left of the point O were accompanied by such deflections. This can be understood as in the following. Suppose that the center of a valley-shaped perturbation occurs at a point to the right of O, so that the decelerating transverse electric fields cause the electron flux to increase at 0-2 cm to the right of O, which will be detected by an x-ray detector looking to the right of O. These decelerating transverse fields will deflect ions originating at the right side of 0 in the $+\theta$ direction. Such ions are likely to pass through the aperture since they originate at the right and are deflected to the left (see the solid line in Fig. 9(b)]. Thus, the experimental geometry is likely to allow the observation of $+\theta$ ion deflections when the slow increases in the electron flux occur right of O. When the perturbation center occurs to the left of 0 the electron flux may increase left of O, thus being detected by the detector looking there. However, since the ions deflected to the left (in the $+\theta$ direction) originate left of O, they may be directed to the left of the aperture, thus not passing through it (this can be seen schematically in Fig. 9(b) where ions deflected in the $+\theta$ direction are almost blocked by the left aperture edge, as depicted by the dashed line). Therefore, $+\theta$ ion deflections are less likely to be observed when increases in the electron flux occur left of O. It is noteworthy, that these limitations imposed on the observation of ion deflection by the experimental geometry, suggest that the correlation between the slow increases in the electron flux and the $+\theta$ class B ion deflections is possibly stronger than the observed 50% reported here.

VII. Additional Results Supporting the Assumption on the Anode-Plasma Role

In a few shots the diode voltage collapsed for several tens of nanoseconds and then recovered as shown in Fig. 12(a). As expected, the ion current density considerably decreased during the voltage collapse

This is shown in the corresponding streak photograph presented in Fig. 12(b), where a dark region is observed during the period of the voltage collapse. On this shot, ions from another portion of the diode (at a distance of 5 cm away in the azimuthal direction) were also viewed using the same aperture geometry. This showed a similarly large reduction in ion current density. It is highly likely that such a decrease in the ion density in the gap was accompanied by a decrease in the electron population in the gap since otherwise the electric field resulting from the imbalance of the charge will exceed considerably the applied field. (Indeed the electron bremsstrahlung signal sharply decreased but this decrease was evidently affected also by the decrease of the electron energy due to the reduction in the diode voltage and not only by the reduction in the electron flux.)

Several characteristics of the streak in Fig. 12(b) are noteworthy. The width of the streak at the start of the dark region is determined by the ion beam transverse velocity spread in the azimuthal direction. Also, the dark region does not start along a straight line, perpendicular to the streaking time direction, because the ion beam divergence in the radial direction varies along the azimuthal direction. Thus, the shape of the streak at the start of its dark region is determined by the ion deflections in both the azimuthal and the radial directions. The same holds true for the end of the dark region as well, when the ion current density rises again. Notice that the streak has the same shape in both the azimuthal and the radial directions at the start and at the end of the dark region. This indicates that the same ion beam deflections before and after the voltage collapse were obtained for both directions. Such a collapse of the diode voltage occurred in three shots and this result was obtained in each of the three cases.

Obviously, the charge distribution in the diode gap must have been significantly disrupted during such a considerable voltage collapse which lasted about 100 ns. However, it is reasonable to believe that the surface of the plasma in the diode could roughly retain its shape during the voltage collapse. This would lead to the production of transverse electric fields at the diodevoltage recovery similar to those just before the voltage collapse. Thus, it seems very likely that the ion direction of motion (and hence the shape of the potential surfaces in the diode gap) are determined, to a large extent, by the shape of the anode plasma. Clearly, this conclusion is in agreement with the role of the plasma shape deduced from our the previous results.

VIII. Summary and Discussion

Local changes in the direction of motion of ions produced in a magnetically insulated diode were investigated simultaneously with the local changes in the electron flux to the anode. Short-duration ion deflections which coincided with short intense electron bursts to the anode were observed. The experimental findings supported the conclusions that these changes in direction occurred in the diode gap, that they resulted from transverse electric fields (not magnetic fields), and that the associated perturbation in the equipotential surfaces were valley-shaped (the surfaces are closer to the anode at the perturbation center). The perturbation size was inferred to be 10-30 mm in the azimuthal direction (E x B drift direction). Since the electron bursts were found to occur in the absence of an anode plasma it is deduced that the presence of anode plasma and ions in the gap is not responsible for the formation of the short-duration transverse electric fields. This potential perturbation could be caused by a local increase in the gap electron density which is also consistent with the simultaneity between the electron bursts and sharp peaks in the ion current density previously reported.

A second type of observation consisted of slow ion deflections most of which could be categorized into two main classes. The deflections of both classes were also shown to occur in the diode gap and to result from electric fields. The results also implied that the perturbations in the fields were caused by slow changes in the shape of the anode plasma surface, rather than due to changes in the electron sheath structure.

In the first class the ion deflections started with a sharp increase in the ion current density. The data indicate that this increase is caused by a local increase in the rate of ion-supply from the anode plasma. The ion beam is source limited rather than space-charge limited. The increase of the rate of ion supply implies local increase in the anode-plasma temperature or density. The transverse electric fields causing the ion deflections are produced by a hill-shaped potential perturbation. It is suggested that such a perturbation results from a local increase in the plasma expansion rate, perhaps due to the excess local heating of the plasma.

The mechanism which leads to a nearly instantaneous increase in the plasma density or temperature is not clear. The experimental findings show that this mechanism is certainly not caused by an increase in the electron flux to the anode. A plausible explanation is that the heating is associated with the return current in the plasma. The average return current density in the plasma (assuming all the diode current flows through it) is about 300 A/cm^2. Assuming a plasma of 1 eV temperature and 10^{16} cm^{-3} density gives a spitzer resistivity of 4×10^{-2} Ω cm. Temporal changes in the anode-plasma resistivity may cause local concentrations of the return current. Such current concentrations may lead to excess heating or additional ionization. For instance, an increase in the return current density by factor 2 for 10 ns may cause an increase in the temperature of a 1 mm-thick plasma (of such a density and resistivity) of the order of 1 eV, i.e., of 100%. Besides the increase in the rate of the ion supply this may cause an increase of a few tens of percent in the plasma expansion velocity. Since the average expansion velocity of the plasma is about 2 cm/μs,[17] it is possible that this results in a local protrusion of about 1 mm (0.1 of the physical gap) in a period of about 100 ns.

The slow ion deflections of the second class were found to result from valley-shaped potential perturbations. The observed decrease in the ion current density supported an explanation that this perturbation was caused by a local depletion of the anode plasma. Slow increases in the electron flux were found to accompany only the slow ion deflections of the second class, i.e., only the valley-shaped potential perturbation. It was also inferred that at least half of these slow increases were associated with such slow ion deflections. It is concluded that these increases are due to the effect of these potential perturbations on the electron flow. Since these perturbations are believed to be caused by the anode-plasma shape, this is in agreement with a previous finding that the slow increases in the electron flux are considerably reduced in the absence of the anode-plasma.[11] Based on an analysis of a single-particle motion we provided an explanation for the fact that only the valley-shaped perturbations (specifically, valley-shaped perturbations which cause large $+\theta$ ion deflections) cause the electron flux to the anode to increase. The explanation points out that the E x B drifting electron which approaches a hill-shaped perturbation first faces accelerating transverse electric forces which leads to an electron motion towards the cathode. By contrast, an electron moving towards a valley-shaped perturbation first encounters decelerating transverse forces, which causes its motion towards the anode. However, a further analysis of the collective electron flow under the influence of both potential perturbations is certainly needed.

We note that the use of a hotter or a denser plasma source at the anode may prevent plasma depletion, thereby eliminating the slow ion deflections of class B and reducing the slow increases in the electron flux to the anode. However, since the mechanism which causes the local increase in the plasma expansion rate is not understood as yet, the use of such a plasma source may not necessarily eliminate the formation of the hill-shaped perturbation and the slow ion deflections of class A.

Acknowledgements

The author acknowledges D. A. Hammer, R. N. Sudan, and C. Litwin for stimulating discussions and thanks D. A. Hammer for careful reading of the manuscript. Valuable comments by J. A. Nation are appreciated. Special thanks to L. Maron for computer programming.

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Figure Captions

Fig. 1 a) Schematic diagram of the LONGSHOT diode and the measurement system. The anode annulus is with 17.8 cm i.d. and 22 cm o.d. The hollow cathode is a ring 22 cm in diameter. The insulating magnetic field is produced by two coils. Ions passed through a circular aperture, and then through a slot before hitting a scintillator sheet photographed by a fast streak camera. X-ray collimators, with scintillators and PM-tubes, viewed portions of the anode, looking through the lucite flange almost perpendicular to the anode.

b) Typical voltage and current waveforms.

Fig. 2 Schematic diagram of the technique used to measure the local ion beam divergence. The horizontal direction on the diagram is the azimuthal direction. The circular aperture and the slot are radially centered with respect to the anode annulus. The direction of the E x B flow is denoted by the arrow e. The diameter of the circular aperture varied from 1.2 to 1.4 cm. The slot was 1 mm wide and 40 mm long in the radial and the azimuthal direction, respectively. Anode-aperture, aperture-slot, and slot-scintillator distances were 4.6 cm, 2.4 cm, and 3 cm, respectively. Deflection of ions in the direction indicated by $+\theta$ means an increase of their transverse velocities in the E x B drift direction.

b) An example of a streak photograph. The light spot at the botom is a static photograph made before the shot. The ion-aperture diameter was 12 mm.

Fig. 3 A streak photogrpah and an x-ray detector oscillograph from a typical shot with a short duration ion deflection. a) The short (about

10 ns) ion deflection in both the +θ and the -θ directions is indicated by the solid arrow. The wide spot in the streak appears to be at an angle with respect to the streak direction because the ion transverse velocities in the radial direction vary along the azimuthal direction. t = 0 marks the start of the voltage pulse. The ion aperture was 14 mm.

b) The corresponding bremsstrahlung signal measured by a detector viewing an anode area 10 mm in the radial by 40 mm in the azimuthal direction . It was centered with respect to the anode area viewed by the ion detector. The dashed arrow and the dashed horizontal line at the left indicate the start of the fiducial mark and the baseline, respectively. The first of the two observed electron bursts (indicated by a solid arrow) coincides with the short ion deflection.

Fig. 4 A diagram of ion trajectories which corresponds to Fig. 3(a). The point O is the center of the anode area viewed by the ion detector through the aperture FG. $\overline{AB}$ and $\overline{CD}$ indicate the scintillator region hit by the ions during and prior to the short duration, wide portion of the streak, respectively. For evaluating α_1 (see text) it is assumed that $\overline{CD}$ is illuminated by ions from the point E (see dashed lines $\overline{CE}$, $\overline{DE}$). Ions reaching the points A and B could originate at any point along the anode sections $\overline{HI}$ and $\overline{JK}$, respectively (as indicated by the solid lines $\overline{AH}$, $\overline{AI}$, and the dotted lines $\overline{BJ}$, $\overline{BK}$, respectively). The solid line ℓ depicts the local shape of potential surfaces which would allow such ion trajectories.

Fig. 5 a) Ion deflections when the center of the potential perturbation ℓ occurs at O_1, located a few millimeters in the $-\theta$ direction from the point O. Ions deflected in the $-\theta$ direction (solid line) are not likely to pass through the aperture in contrast to ions deflected in the $+\theta$ direction (dashed line). $\overline{LM}$ and $\overline{NP}$ are two circular anode regions, 15 mm in diameter, each of them viewed by a different x-ray detector, X_1 and X_2, respectively.

b) A short ion deflection (see arrow) only in the $+\theta$ direction. It coincided with an electron burst observed only by the detector X_2 viewing the area $\overline{NP}$. The increase in light intensity at the end of the streak is mostly instrumental, thus will be always ignored.

Fig. 6 a) A streak photograph showing a sharp increase in the ion current density (indicated by the arrow), at which time an ion deflection (of class A) in the $+\theta$ direction starts growing. It continues to grow until the end of the streak. The ion aperture diameter was 14 mm.

b) A diagram of a hill-shaped perturbation in the potential surfaces ℓ and the resulting ion deflections. The perturbation center occurs at the center O of the area viewed by the ion detector. The arrows labeled e and F_t indicate the E x B drift direction and the direction of the transverse electric force on an electron approaching the perturbation, respectively (see Sec. V).

c) The perturbation center occurs at O_1, a few millimeters (in the $+\theta$ direction) from the point O.

Fig. 7 A streak photograph showing a relatively large ion current-density J_i over a region of the diode a few millimeters in size. The large J_i is seen at the beginning of the streak on the right side, and it lasts more than 100 ns.

Fig. 8 a) An ion deflection of class A (starting at the arrow) in a case in which the streak widens in both directions. The deflection angle in both the $+\theta$ and the $-\theta$ directions is ~3°.

b) Deflections in the $-\theta$ direction at both sides of the streak. The deflections at the left and the right side grow to ~5° and 11°, respectively.

c) An ion deflection in case when the entire streak bends in the $+\theta$ direction. The deflection grows to 15° on both sides of the streak. The ion aperture diameter was 14 mm in all three cases.

Fig. 9 a) Slow ion deflection of class B. The deflection (starting at the arrow) grows for about 100 ns. The current density is low in the central part of the streak throughout the deflection duration, as indicated by the absence of light from the scintillator.

b) Diagrams ℓ of valley-shaped perturbations in the potential surfaces . The solid lines indicate a perturbation centered at the center O of the area viewed by the ion detector and the resulting ion trajectories. The dashed lines correspond to a perturbation centered at the point O_1, a few millimeters from O. Observation of large ion deflections simultaneously in both the azimuthal directions, even for the perturbation centered at O_1, is possible. The arrow e indicates the E x B drift direction and the arrow F_t the direction of the transverse force on an electron approaching the perturbation (see Sec. V).

Fig. 10 Bremsstrahlung signals obtained by two detectors from the shot for which the streak photograph is shown Fig. 7(c). One detector (upper trace - negative signal) viewed an anode region 15 mm wide in the radial direction and 23 mm in the azimuthal direction. The other detector (lower trace - positive) viewed a region 12 mm by 40 mm. Both areas were centered with respect to the area viewed by the ion detector. The dashed lines indicate the baselines. The arrows indicate the instant the ion deflection started [see Fig. 7(c)]. The fiducial marks appear at the end of the oscillographs.

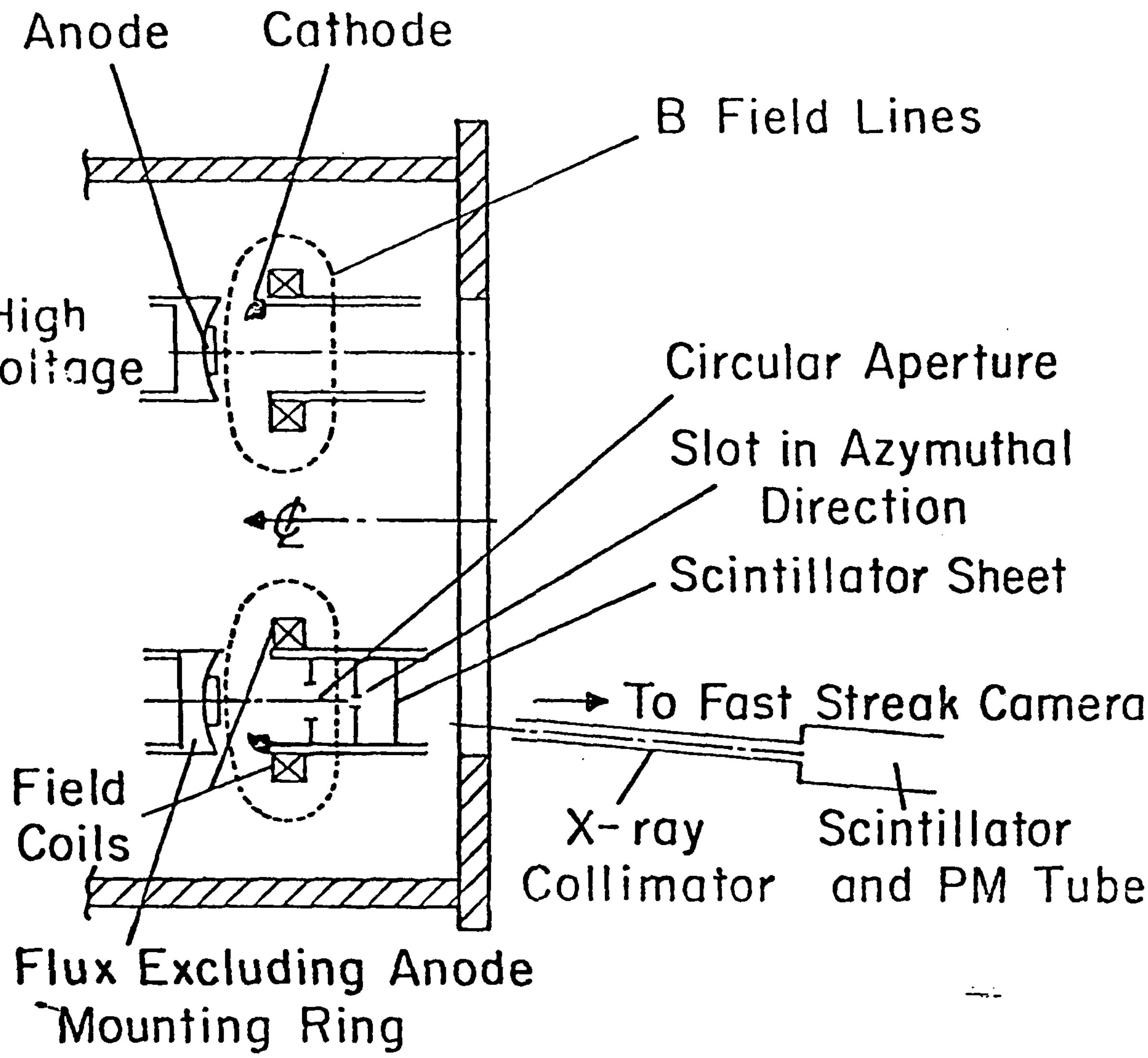
Fig. 11 a,b) A class B ion streak photograph and the corresponding electron flux to the anode. The ion aperture diameter was 14 mm and the x-ray detector viewed a 15 mm diameter region to the right of the ion aperture center, as indicated by the line $\overline{NP}$ in Fig. 5(a). The dashed line at the left in b) indicates the baseline. An ion deflection of class B in the $+\theta$ direction starts after a short ion deflection which is indicated by the solid arrow. The streak width then increases and the light intensity is weak in the middle. The small electron burst (solid arrow) coincides with the short ion deflection at the start of the slow deflection. The dashed arrows indicate an additional short deflection and a simultaneous sharp electron-flux rise.

c,d) An additional class B example. The ion aperture diameter was 10 mm. The x-ray detector viewed an anode area of 12 and 40 mm in the radial and the azimuthal direction, respectively, which was centered with respect to the ion aperture. The arrows indicate the start of the $+\theta$ ion deflection and the start of the simultaneous rise in the bremsstrahlung signals. The fiducial marks on the bremsstrahlung signals appear at the end of the oscillographs in both b) and d).

Fig. 12 a) An example of a diode voltage waveform in which a relatively sharp voltage decrease (starting at the arrow) which lasts for ~100 ns is observed. The fiducial mark appears at the end of the oscillograph.

b) The corresponding streak photograph showing a considerable reduction in the ion current density (starting at the arrow) during the voltage decrease. The contour of the light intensity just before and after the reduction in J_i are similar in both the radial and azimuthal directions. The ion aperture diameter was 12 mm.

a)


Anode
Cathode
B Field Lines
High Voltage
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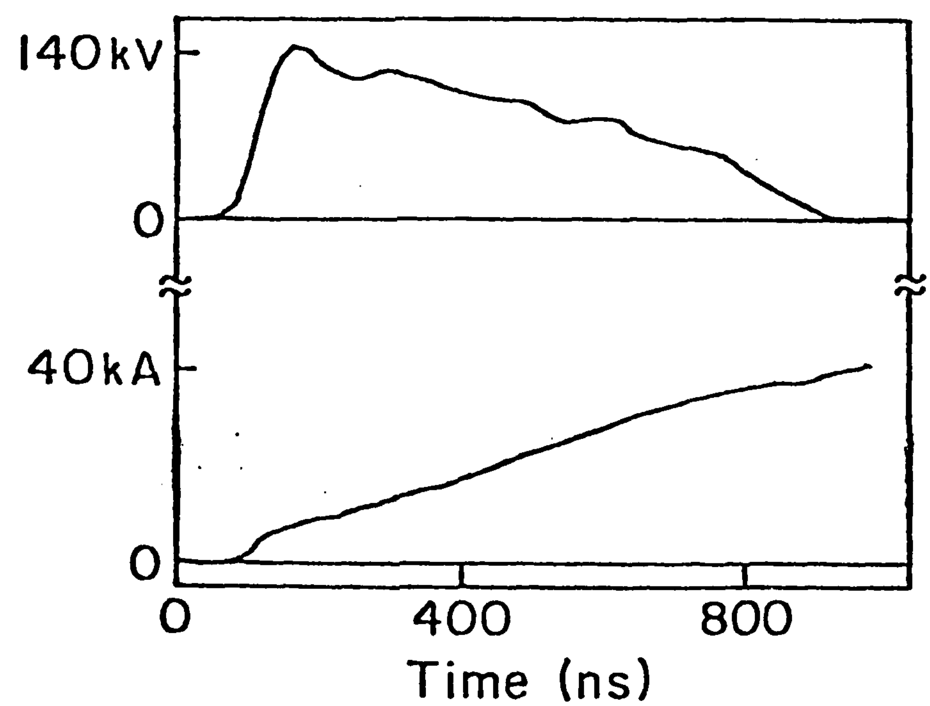
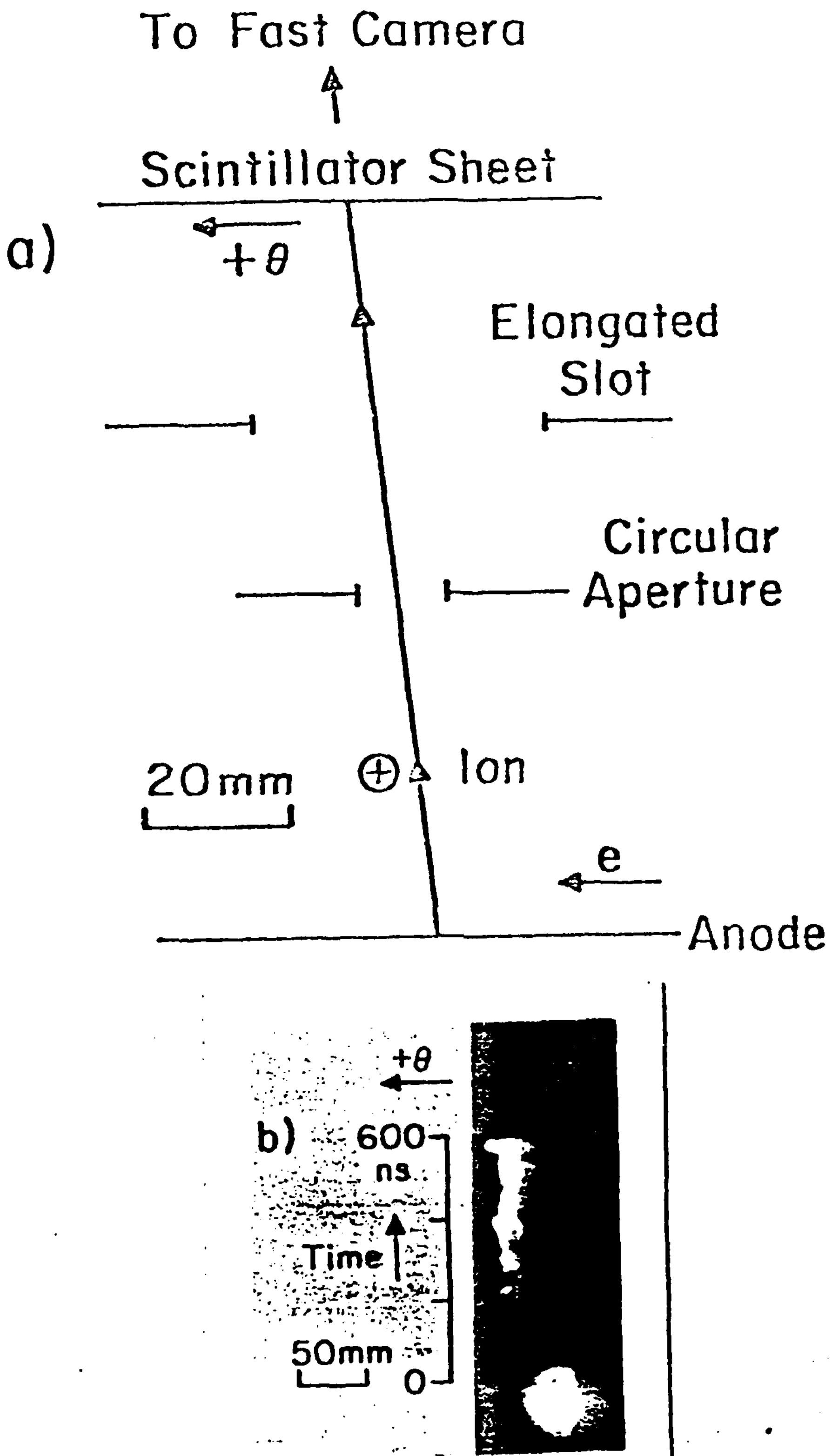
Slot in Azymuthal Direction
Scintillator Sheet
To Fast Streak Camera
Field Coils
X-ray Collimator
Scintillator and PM Tube
Flux Excluding Anode Mounting Ring

b)


140kV
0
40kA
0
0
400
800
Time (ns)



To Fast Camera
Scintillator Sheet
a)
+θ
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b)
600 ns
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Figure 2

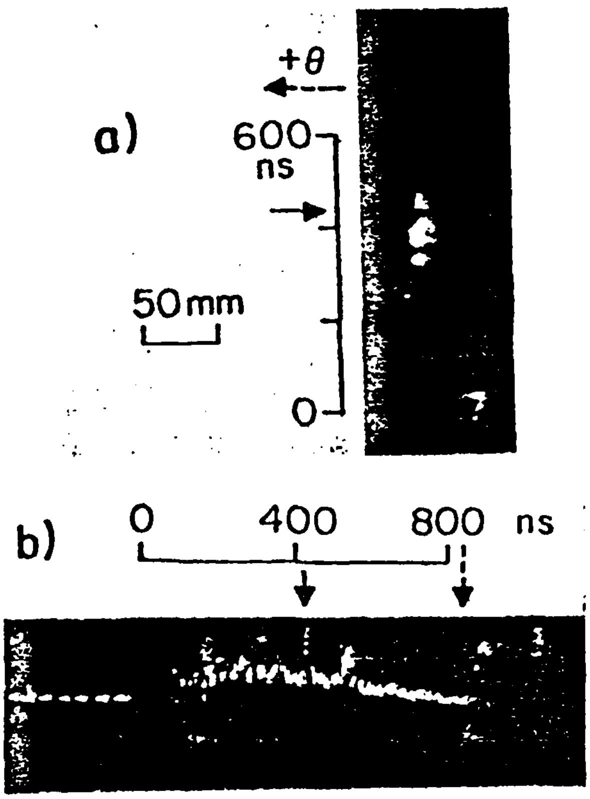
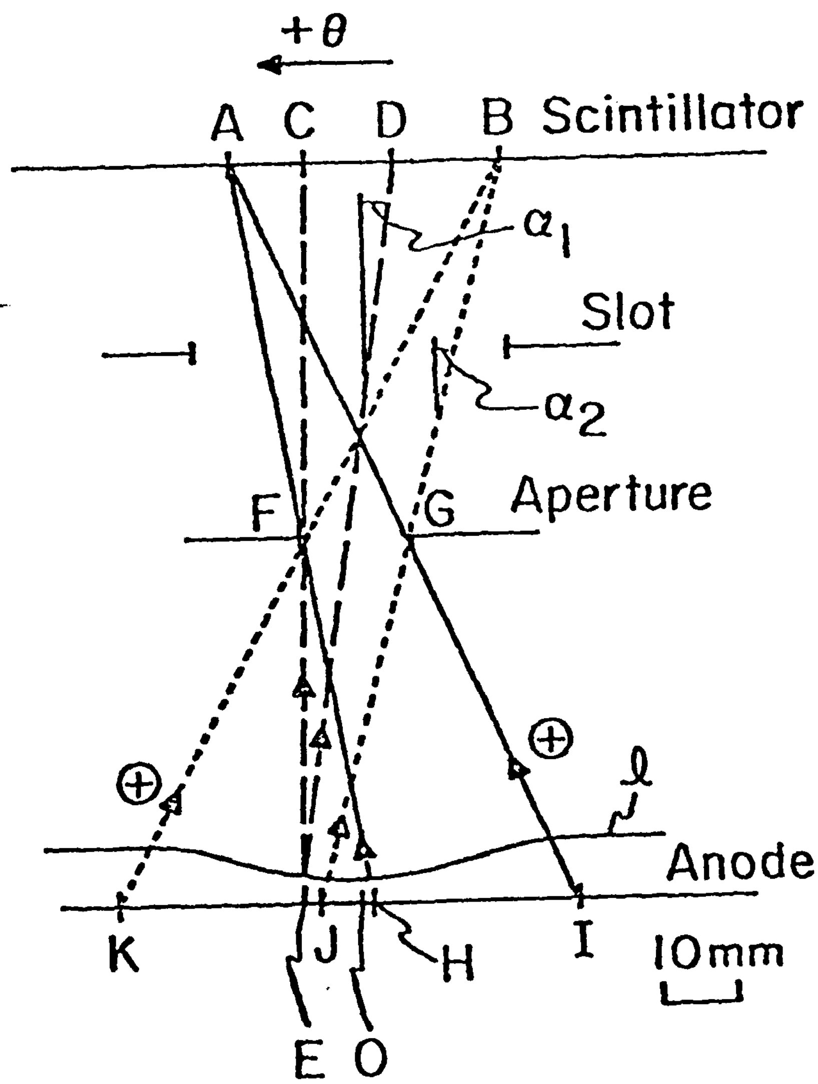


Figure 3



+θ
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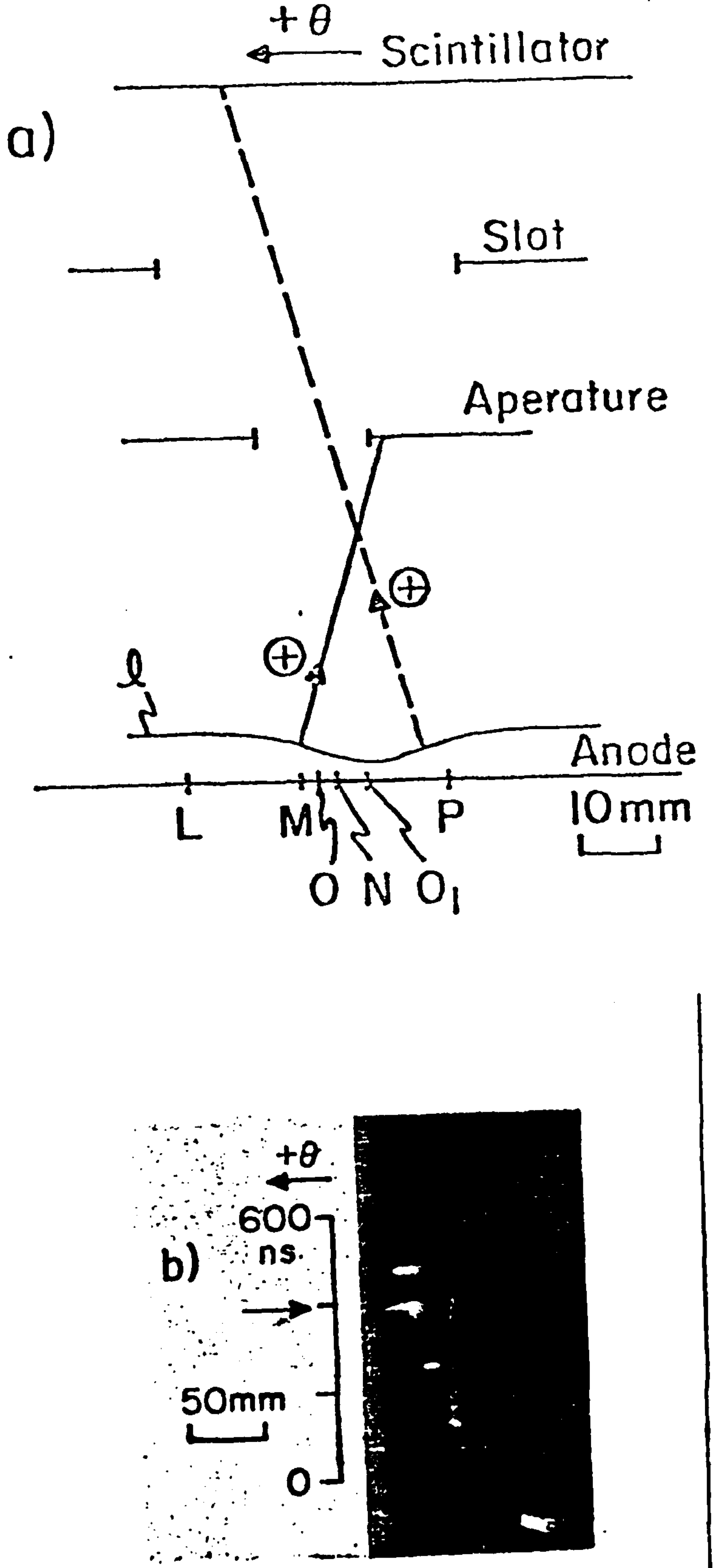
Figure 4



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b)
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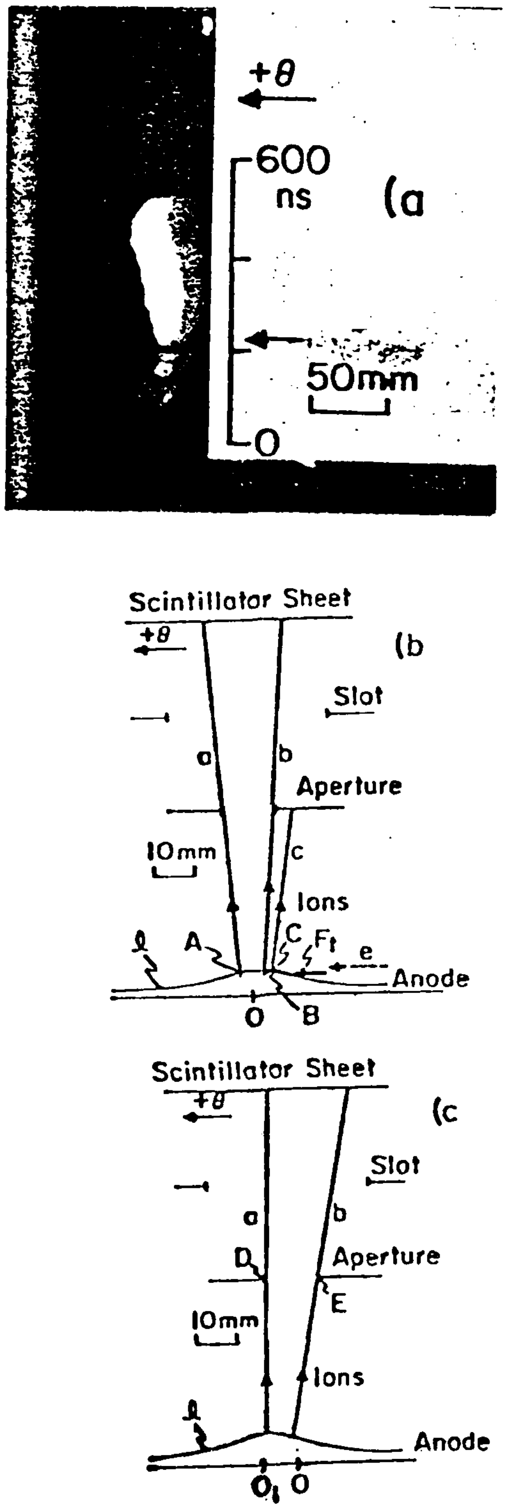
Figure 5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Ft
e
Anode
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Ions
Anode
O1
O

Figure 6

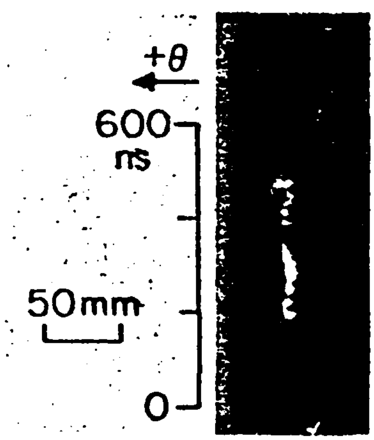

Figure 7

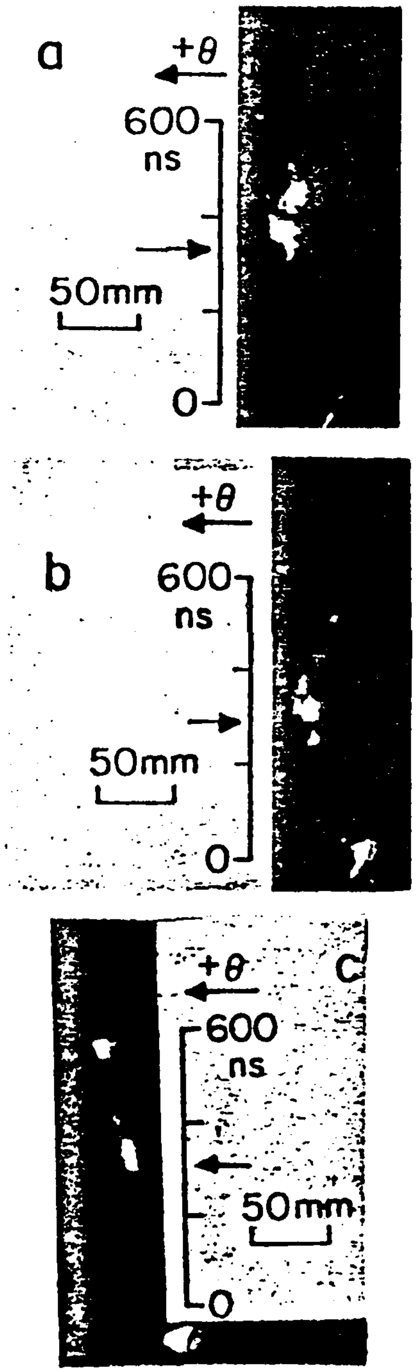

Figure 8

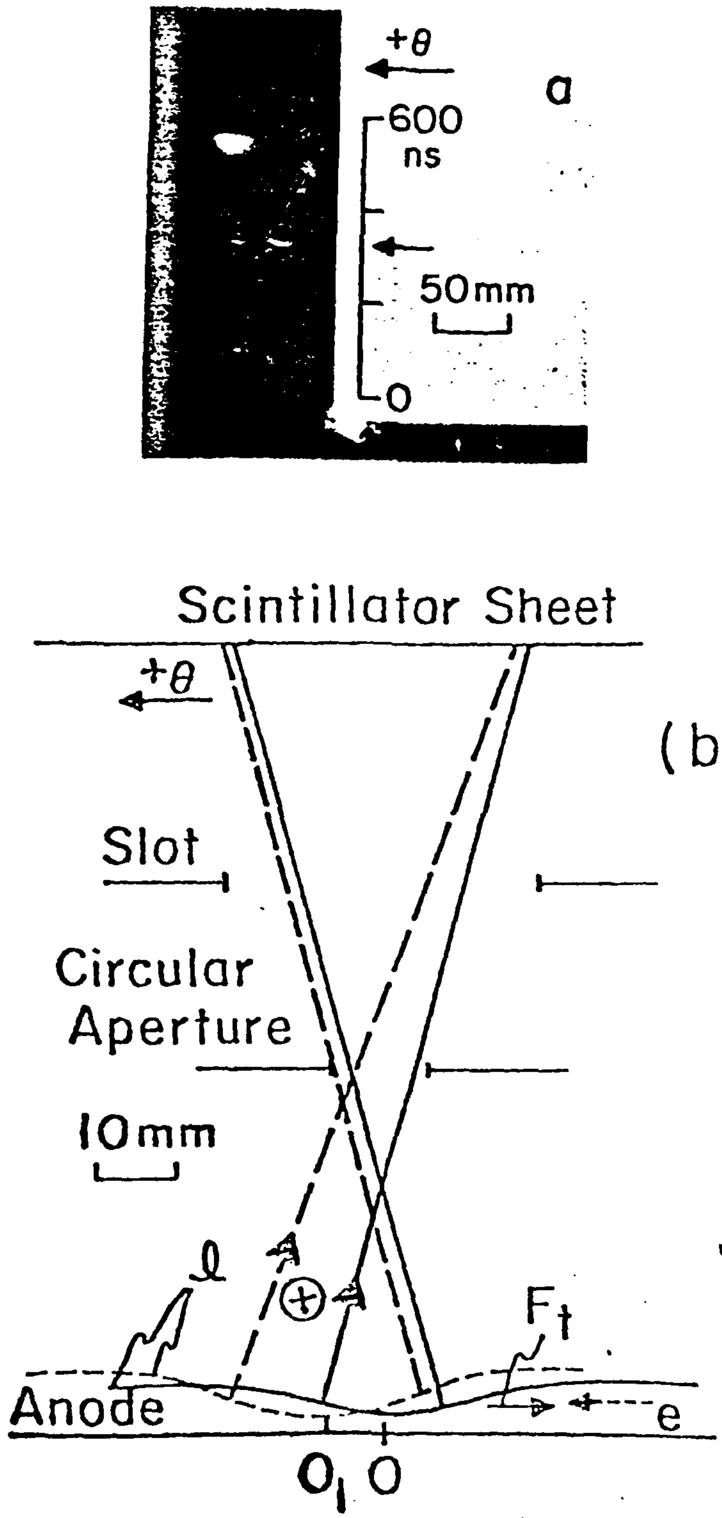
+θ
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Figure 9

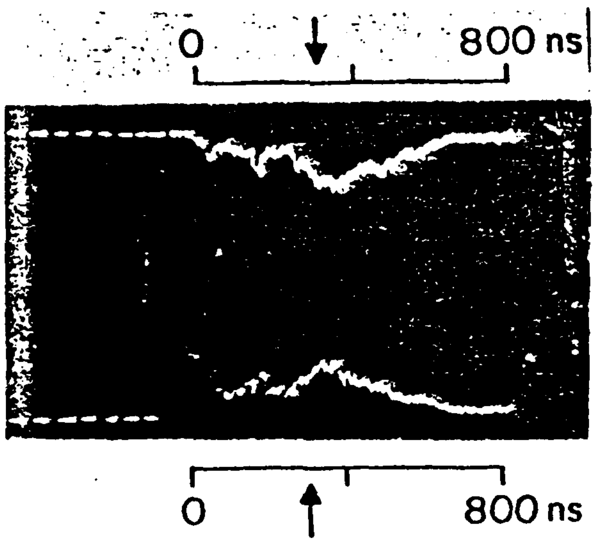

Figure 10

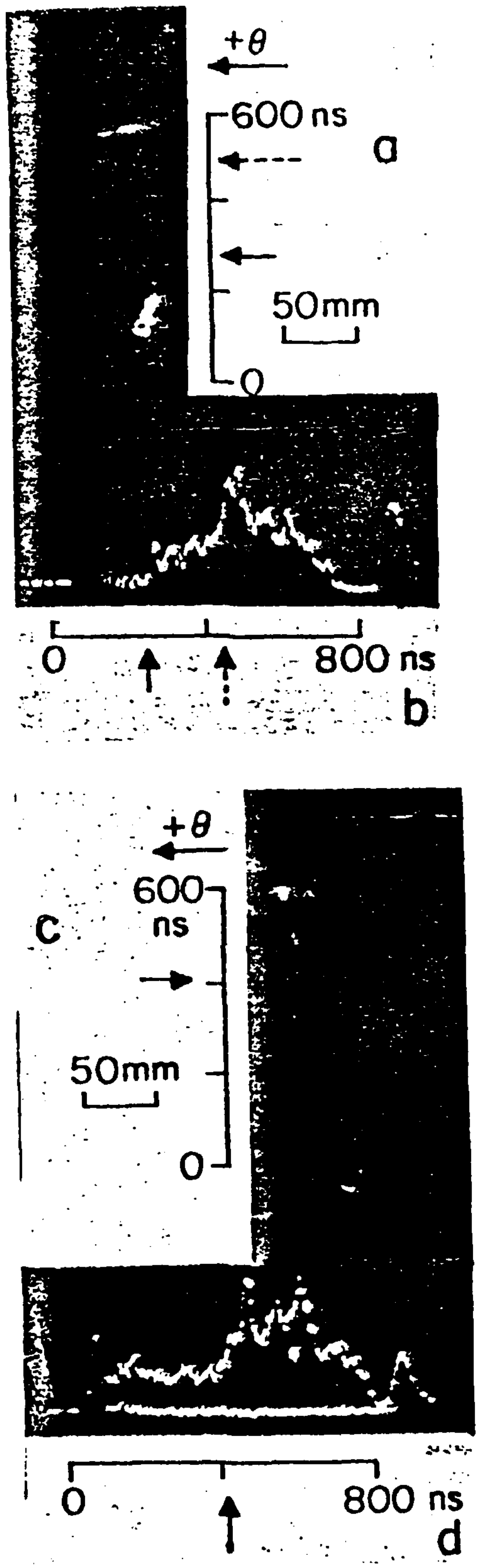

Figure 11

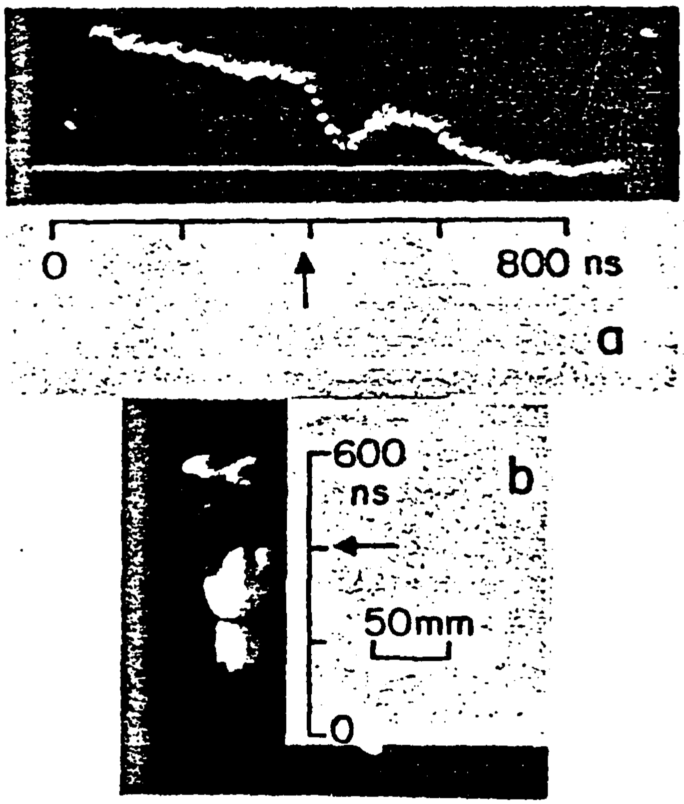

Figure 12