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Angular Distribution of Electrons in the Pinch Region of Relativistic-Electron-Beam Diodes

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Pinhole bremsstrahlung photography was used to measure the angular distribution of electrons incident on the anode in the pinch region of relativistic-electron-beam diodes. It was found that the incidence angles of most of the electrons are limited to 30° with the diode axis and that the average electron direction at each point within the pinch is nearly parallel to this axis. These results may imply quite strong electric fields in the vicinity of the pinch.

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It is well known that intense relativistic electron beams in large–aspect-ratio diodes are focused at the anode center forming a pinch of several millimeters in diameter.[1-3] Electrons emitted at large radii of the cathode converge to the anode center because of combined $\vec{E}\times\vec{B}$ drift motion and Larmor rotations.[4,5] Analytic models[4,6] or simulation codes[7] describe satisfactorily the charge flow at large radii of the diode. However, because of the complexities characterizing the pinch region, no reliable predictions about the charge distribution or the electron trajectories at the diode center are as yet available. Therefore, factors determining the pinch size are not completely understood.[8-10] A study of the pinched electron flow is also important for the understanding and design of diodes producing intense ion beams for pellet fusion.[11] In this work the electron directions of motion as they reach the anode in the pinch region are studied, by use of pinhole photography.

An electron beam generator[12] was used to produce a 100-ns electron beam pulse with a 30-ns rise time. The cathode,[12] sprayed with Aerodag, was 80 mm in diameter, with the center 14-mm diameter recessed by 15 mm and the outer 20-mm radius tapered at 6°. The anode was 0.5-mm-thick aluminum and the anode-cathode gap was ~3.5 mm. Typical voltage and current traces are shown in Fig. 1(a). The pinhole used[13] was of a hyperbolic cross section and 0.35 mm in diameter. A hole of 0.6 mm diameter was drilled in the anode center. The shape of the hole was that of a truncated cone with half-angle in the range

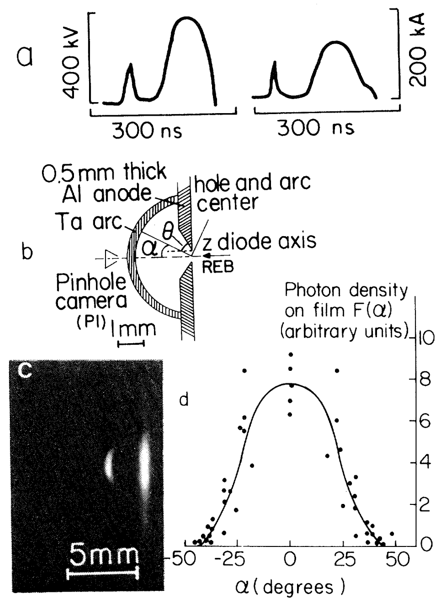

FIG. 1. (a) Voltage and current traces (fiducial marks preceding). (b) A side view of the anode and the arc. (c) An arc photograph obtained by camera $P2$ in a well-centered shot with an arc radius $R = 2.4$ mm. (d) Film density $F(\alpha)$ of arc photographs obtained from five identical shots.

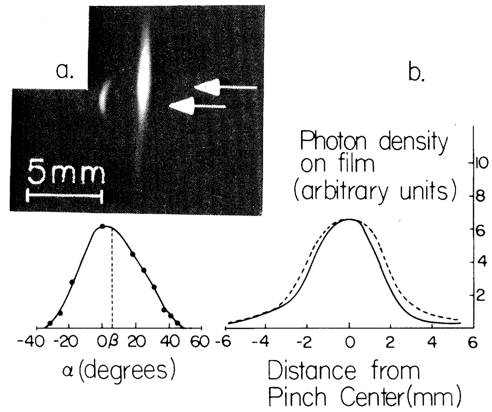

FIG. 2. (a) Photograph obtained by the camera $P2$ in a shot where the pinch center (indicated by the upper arrow) occurred at a distance 1.1 mm from the hole center (lower arrow) and the corresponding angular distribution. (b) Density profiles of pinches, produced in two identical shots on 0.5-mm-thick flat Al anodes, as obtained with the on-axis pinhole camera.

$\theta = 45°-70°$ [see Fig. 1(b)]. This shape minimized the interaction of electrons passing through the hole with its walls. A tantalum arc having the shape of an equatorial section of a sphere 25 μm thick and ~2 mm wide was attached to the rear surface of the anode. The arc symmetry axis coinsided with the diode axis (z) and its center lay at the anode hole center. Arc radii of 1.5–3 mm were used. A pinhole camera ($P1$) looked at the anode along the diode axis. Another camera (**P**2—not shown in Fig. 1) was placed at 90° to the diode axis, viewing the arc from the side. The 0.5-mm-thick Al anode was sufficient to stop the 390-keV electrons[14] and only a small portion which passed through the hole could hit the arc. The relative film density F at each point of the arc was recorded by camera **P**2. It is given in Fig. 1 as a function of the angle α along the arc. In the geometry employed the film density $F(\alpha)$ is proportional to the flux of the electrons reaching the arc, thus giving the angular distribution of these electrons. This angular distribution of electrons is similar to that just inside the diode provided that the fields outside the diode are sufficiently small. Charge neutralization was achieved by introducing air of 1–4 Torr in the drift tube.[15] The anode hole was sealed with a 6-μm aluminized Mylar sheet over the anode surface. Detailed calculations showed that self-magnetic fields over a distance of very few millimeters could alter the direction of the electrons by a few degrees only, since the emerging beam current was ~1 kA, as determined from measurements to be discussed later.

It can be seen in Fig. 1 that the angular distribution of the electrons incident near the anode center is peaked forward and that the incidence angles of two-thirds of these electrons are limited to angles $\alpha \lesssim 30°$ with the diode axis. Calculating the average $\langle \cos\alpha \rangle$ for $F(\alpha)$ shows that the average fraction of the electron momentum in the axial direction is ~0.9. Such results were obtained in a large number of experiments. Corrections due to the spatial resolutions of the camera and the densitometer would result in an angular distribution narrower by a few degrees. Furthermore, accounting for the electron scattering by the anode plasma or the Mylar window would also narrow this distribution.

When the pinch center did not coincide with the hole center, the angular distribution at off-center points of the pinch was obtained. An arc photograph, obtained when the distance between the centers of the pinch and the hole was 1.1 mm, and the corresponding angular distribution are shown in Fig. 2. For comparison the pinch size is also given, as shown by the profile of a pinch produced on a 0.5-mm-thick flat aluminum anode.

The measured angular distribution is similar to that of the centered pinch shots. However, the average direction β, defined as the average angle $\langle\alpha\rangle$ of the distribution $F(\alpha)$, points inward (towards the pinch axis) at $\simeq 6°$. Similar results were also obtained when the hole center was located at distances $\gtrsim 1.2$ mm from the pinch center. The values of β were less than 10°, always pointing inward. When the hole center was at distances of ~2 mm from the pinch center, the measured angular distributions were wider by a few tens of degrees and the values of β increased up to 20°.

In order to establish what fraction of the electrons hitting the anode hole emerge outside the diode, the arc was removed and an aluminum plate, 0.5 mm thick, was placed parallel to the anode at a distance between 1 and 4 mm from it. This "back plate" was mounted on a conducting cylinder which was grounded outside the drift tube, as shown in Fig. 3(a). A Rogowski coil measured the current collected by the back plate. A pinhole camera, placed at 54° to the diode axis, simultaneously viewed the anode hole in the pinch region and the area of the back plate hit by the emerging electrons. Film density profiles of the pinch and of the beam spot on the back plate were measured as shown in Fig. 3(b). The integral film density missing over the hole area in the anode was estimated. By comparing this quantity with the film density integrated over the back-plate spot, it was found that practically all electrons incident on the anode hole reached the back plate. Therefore, the measured angular distribution represents the distribution of the majority of the electrons reaching the hole. The measurements of the collected current (with no air in the drift tube) yielded a value of ~1 kA in agreement with an estimate based on Ref. 3, where a diode similar to ours was used.

Several experiments were carried out to study the sensitivity of these results to certain parameters. Thus, varying the angle θ of the anode-hole cone between 45° and 70° did not alter the angular distribution. Varying the cathode recess diameter, which was found to affect the pinch size,[16] from 14 to 30 mm gave no changes in the former results. Coating the anode center with polyethylene, thus increasing light-ion density, did not alter the results. The influence of electron backscattering from high-Z anodes, which was found to increase the pinch size,[10] was studied using tantalum anodes. Angular distributions broader by ~10° were observed. It is not clear

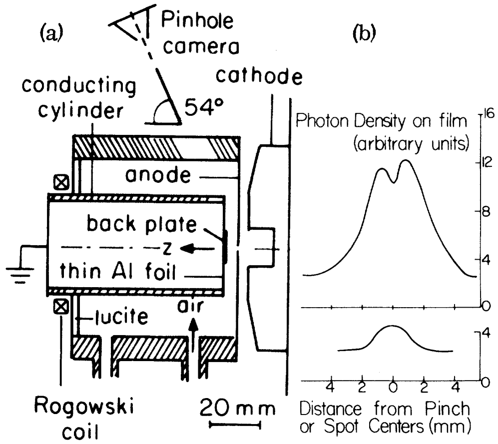

FIG. 3. (a) Schematics of the system in the back-plate shots. The back plate is mounted on a 40-μm Al foil stretched over a conducting cylinder. (b) Density profiles along the diameter of the pinch (top) and of the back-plate spot (bottom). A hole of 1 mm diameter is at the anode center.

whether this broadening was due to backscattering or to scattering of outgoing electrons by the high-Z plasma.

The electron angular distribution measured here was obtained from a direct measurement. This distribution is much narrower than that deduced from measurements of bremssrahlung angular distribution.[10]

One possibility to explain the nearly axial electron motion in the pinch region of the diode is to assume strong electric fields there. Let us consider the case of a strong axial component E_z accelerating the electrons near the anode. Roughly speaking, such an E_z should be at least equal (in cgs units) to the magnetic field B_θ. The measurements of the emerging current give a current ~25 kA in the central 3-mm-diam region of the pinch. The corresponding field is then $B_\theta \gtrsim 30$ kG, an order of magnitude higher than the diode average electric field $\bar{E}_z \simeq 3.6\times10^3$ statvolt cm^{-1}. Also, for axial motion to occur, the velocity at the anode should be considerably high with respect to the electron velocity prior to encountering this final axial acceleration. Hence, the electrons must require most of their final kinetic energy close to the anode surface. A field $E_z \approx 10 \times \bar{E}_z$ extending over a distance of a few tenths of a millimeter from the anode is adequate. Such an E_z can support space-charge-limited flow of the electron pinch current. Another possibility to be considered is that the electric force has a radially diverging component eE_r. An electron which moves axially, and is subjected to a radial field $E_r \simeq \beta_z B_\theta$, can maintain its direction of motion since the magnetic forces are balanced by the electric ones. It would be interesting to examine whether a narrow angular distribution also occurs for higher pinch currents and therefore stronger fields.

The pinch plasma, moving at a velocity of 3.5 cm/μs,[17] expands during the beam pulse by ~1.5 mm. A narrow electron angular distribution precludes the penetration of most of the beam magnetic field into this plasma since, otherwise, the small electron gyroradius (<1 mm) would not allow the electrons to maintain their axial direction of motion. An estimate[18] of plasma conductivity of several hundreds of mho cm^{-1}, obtained assuming a plasma density of 10^{19} cm^{-3} and a plasma temperature of several electronvolts, is consistent with this conclusion.

Current density distributions in the pinch area can be deduced from profiles of pinhole bremsstrahlung photographs, provided that corrections are made for large variations in electron incidence angles within the pinch.[10] The fact that the angular distribution does not vary much over most of the pinch region means that such corrections are not necessary.

The above results were obtained with similar diode configurations. More measurements with other diode geometries and impedances are needed.

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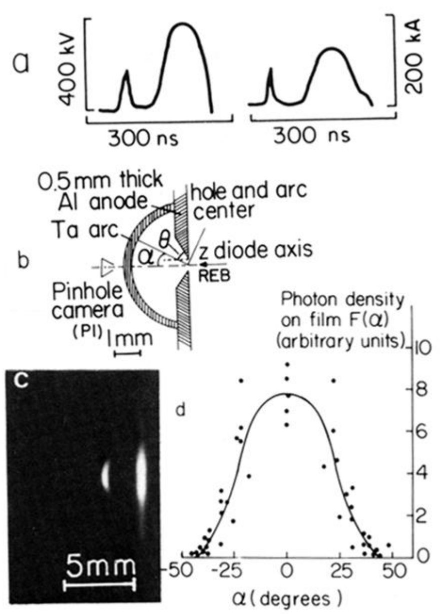

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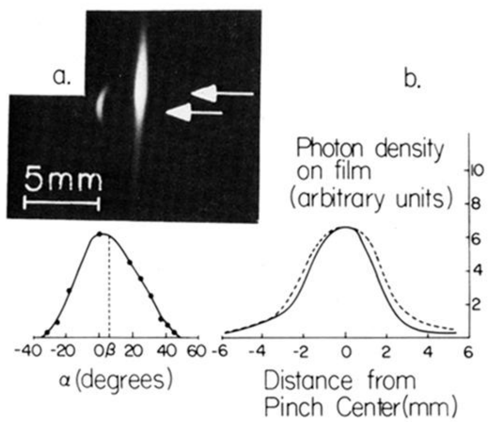

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