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LLL EXPERIMENTS IN COLLECTIVE FIELD ACCELERATION

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LLL EXPERIMENTS IN COLLECTIVE FIELD ACCELERATION*

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INTRODUCTION AND SUMMARY

A collective field accelerator (CFA) has been developed at the Lawrence Livermore Laboratory (LLL) which operates with a vacuum diode.[1-3] This diode utilizes a graphite cathode and a dielectric anode that operates with a relativistic electron beam with a ν/γ of ~ 1. Dielectric lenses are used to focus the collectively accelerated electrons and ions which are ejected from a central hole in the anode. The dielectric anode and lenses operate as unoptimized rf cavities which modulate and focus the beam.[4] Diode experiments aimed at directing and stabilizing relativistic plasma filaments have led to appreciably higher ion energy.[5]

Our CFA experiments have been conducted with the LLL Pulserad 422 e-beam machine which delivers $\sim$ 2.5 kJ at 1 M volt to the diode in 50 ns.

*To be presented by Professor Charles Wharton of Cornell University at the Conference on Plasma Heating, Verona, Italy, September 6-17 1976, as part of the USA presentation on e-beam reactors.

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The pertinent results are: maximum proton energy > 45 MeV, number of protons ∿ 10^{14} per burst, heavy ion energy 7 MeV per nucleon, DD neutrons > 10^{11} per burst, p,n neutrons > 10^{10} per burst. Of the nuclear reactions which occur twenty-eight have been verified through radionuclide identification using a Ge-Li detector. These nuclides were produced with carbon and fluorine ions impinging on Al, Cu and Ta targets.[6] A large number of proton and deuteron reactions have also been verified.

STATUS OF THE LLL - CFA PROGRAM

The results quoted above were achieved using the configuration shown in Fig. 1. To the left is shown the stainless steel cathode shank which is part of the e-beam machine diode. The length of this device is adjustable so that rapid changes in machine impedance can be made. A graphite transition piece is mounted in the end of the cathode shank. The tip of this transition piece is replaceable and forms the actual cathode. The cathode is grooved to help form filamentary current carriers which are guided in a path that causes a large fraction of their energy to be deposited in the target. While moving on the cathode the electrons are space charge neutralized probably due to the presence of slow ions. However, upon leaving the cathode and entering the vacuum gap, space charge neutralization is diminished and the electron stream expands with a portion striking the dielectric anode which produces a plasma pulse.

Ions from the plasma neutralize the electron space charge and the beam compresses and flows through the anode hole. This process occurs several times during one machine pulse producing a number of beam pulses. Ions are trapped by this space charge process and are accelerated, perhaps with the propagation velocity of the filaments which are formed on the cathode. If the cathode is not designed to guide these filaments they tend to pass through the anode hole and rapidly diverge with most of their energy being deposited in components and chamber walls rather than in the ions. In this operational mode the maximum ion energy is < 50% of the observed ion energy with a grooved cathode. Focusing of the beam has been improved by the use of dielectric lenses which to a certain extent function like the insulated anode. Somewhat higher ion energy also results from their use. The target is mounted on a long insulator which causes it to charge to a high negative potential due primarily to impingement of current carrying filaments. This charge accelerates the ions to higher energy.

Figure 2 shows the flow of plasma when lenses are not used and Fig. 3 shows the focusing achieved with a self charged electrostatic lens* and Fig. 4 illustrates the focusing achieved with three lenses. The electrons are well focused on the axis as shown by the spot on the target, however the ions are more divergent. Figure 5 shows the very wide divergence of undirected filaments which have passed through the

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*The light seen on the right-hand side of this picture is reflection from the plasma.

anode hole. Very few of these filaments reach the rear target assembly and under these conditions the target insulator shield is essentially unmarked. Figure 6 shows the markings on the target shield when the filaments are directed along the axis and strike the target. The unusual shape of the resultant patterns is due to the filaments forcing themselves through the small aperature between the shield and the insulator. They assume an elliptical shape in order to pass through cracks.

Figure 7 shows the rear target assembly. The dotted lines indicate the approximate path of the filaments which pass directly through the two-foot insulator.

FUTURE RESEARCH PROGRAM

The foregoing is a brief description of the status of the LLL CFA experimental program. While the results have been encouraging, many fundamental questions remain unanswered. In particular, the role of the plasma filaments must be understood. Theoretical studies are in progress and some tentative ideas are being considered. It is worth noting that these filaments differ from those described in the literature in that the electrons are relativistic. Electrons of one to six MeV were used in the experiments described.

The configuration of a pair of filaments is shown in Fig. 8. The vorticity $\underline{\omega} = 1/2\ \underline{\nabla} \times \underline{u}_e$ ($\underline{u}_e$ = electron mean velocity) in a filament is along the filament axis; ω and the component B_z (in the direction) of the self-consistent magnetic field have a large value within a filament. Onset of vorticity $\underline{\omega}$ and generation of B_z shape the filament and are directly related to each other since angular momentum in the particle flow is not conserved; a linear combination of $\underline{\omega}$ and $\underline{B}$ is. The pairing of filaments is observed, and this pairing is consistent with an equilibrium configuration which is determined by filament magnetic attraction and charge-induced repulsion.

The high-density current channels $\gtrsim 10^4 - 10^5$ A/cm^2, which are observed in the LLL relativistic electron-beam experiments are apparently formed by several current filaments in which electron flow and self-consistent magnetic fields parallel each other along helical lines with a pitch that increases near the filament axis. This typical structure of high-density currents can be described analytically by showing that the electron current carriers are bound to magnetic-field lines, and the positive ions which provide partial charge-neutralization are free to cross these lines. The B_z magnetic-field intensity along the filament axis is of the same order of magnitude as the field due to the total current in the channel. Each filament can in turn separate into smaller units with similar helical field structures and stabilized parameters. Energy balance, among other factors, is controlled by coherent emission and reabsorption of EM radiation within the filament.

The accelerating mechanism which produces high energy ions in the LLL collective field accelerator is not well understood. A suggested hypothesis is that ions are trapped in the anode region by a group of about eight filaments which are directed through the anode hole in pulses of a few ns duration. It is postulated that ions are trapped from the anode plasma due to the field produced by the filament bunch. These filamentary projectiles should be capable of propagation as described below.

Figure 9 shows the visualization of one of the segments of a REB-plasma vortex filament, with electron-velocity ($\underline{u}_e$) configuration in a frame of reference where $\underline{u}_e$ at the periphery is entirely in the θ direction. The continuous establishment of new B_θ and B_z at the tip (and eventually their disappearance at the tail if segmentation of the filament actually occurs) can be considered to be accomplished by the flow of $\underline{E} \times \underline{B}$ or by the induced E_z and E_θ which turn $\underline{u}_e$ from axial in the body to azimuthal at the tip (and vice versa at the tail). The magnitude of the electron velocity $|\underline{u}_e|$ will everywhere be about equal to c; the electrons on the axis have all their velocity in the z direction and the electrons on the periphery have much of that velocity directed in the θ direction. From this it can be shown that $\underline{\omega}$ will increase if B_z is increased and acceleration will be enhanced. On this basis it is postulated that the presence of a large applied B_z field may enhance the acceleration of ions. A B_z field should also improve focusing and reduce instabilities and turbulence. For these and other reasons a pulsed magnetic system has been built using the dielectric focusing lenses as coils. This device is shown in Fig. 10. In addition to providing a guide field it can also be used to produce one or more cusps for focusing or for containment in pellet or plasma compression experiments.

The distance between the coils can be varied at will and various combinations of cusp and linear fields can be achieved. This device will also be used for rf acceleration studies in accordance with the hypothesis that dielectric lenses act as rf cavities.

Table I shows the isotopes produced about a about a year ago using carbon and fluorine ions with an energy of $\sim$ 7 MeV per nucleon which were impinged on Al, Cu and Ta targets. Future experiments will involve focusing and compression studies using ions of the heavier elements. Figure 11 shows a hole 1 mm diam × 1 cm depth bored by our collectively accelerated beam. Such small diameter high density beams may be useful in fusion experiments.

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RADIO–NUCLIDES IDENTIFIED IN LLL COLLECTIVE–FIELD ACCELERATOR EXPERIMENTS

Accelerated Particle	Target	Radio-Nuclide Produced	Accelerated Particle	Target	Radio-Nuclide Produced
C^{12}	$A1^{27}$	C^{11}	C^{12}	Mo	Rh^{98}
C^{12}	$A1^{27}$	$C1^{34m}$	C^{12}	Mo	Rh^{99m}
F^{19}	$A1^{27}$	Sc^{43}	C^{12}	Mo	Pd^{99}
F^{19}	$A1^{27}$	Sc^{44m}	C^{12}	Mo	Ag^{103}
C^{12}	Cu	Ga^{67}	C^{12}	Mo	Ag^{104}
C^{12}	Cu	Cr^{69}	F^{19}	Mo	In^{108}
C^{12}	Cu	As^{70}	F^{19}	Mo	In^{109}
C^{12}	Cu	As^{71}	F^{19}	Mo	In^{110m}
C^{12}	Cu	As^{76}	C^{12}	Ta^{181}	Pt^{189}
C^{12}	Cu	Se^{73}	C^{12}	Ta^{181}	Au^{188}
C^{12}	Cu	Br^{74}	C^{12}	Ta^{181}	Au^{189m}
C^{12}	Cu	Br^{75}	C^{12}	Ta^{181}	Au^{190}
F^{19}	Cu	Kr^{79}	F^{19}	Ta^{181}	$T1^{194}$
F^{19}	Cu	Rb^{81}	F^{19}	Ta^{181}	Pb^{195m}

FIGURE 1 PRESENT CFA SYSTEM

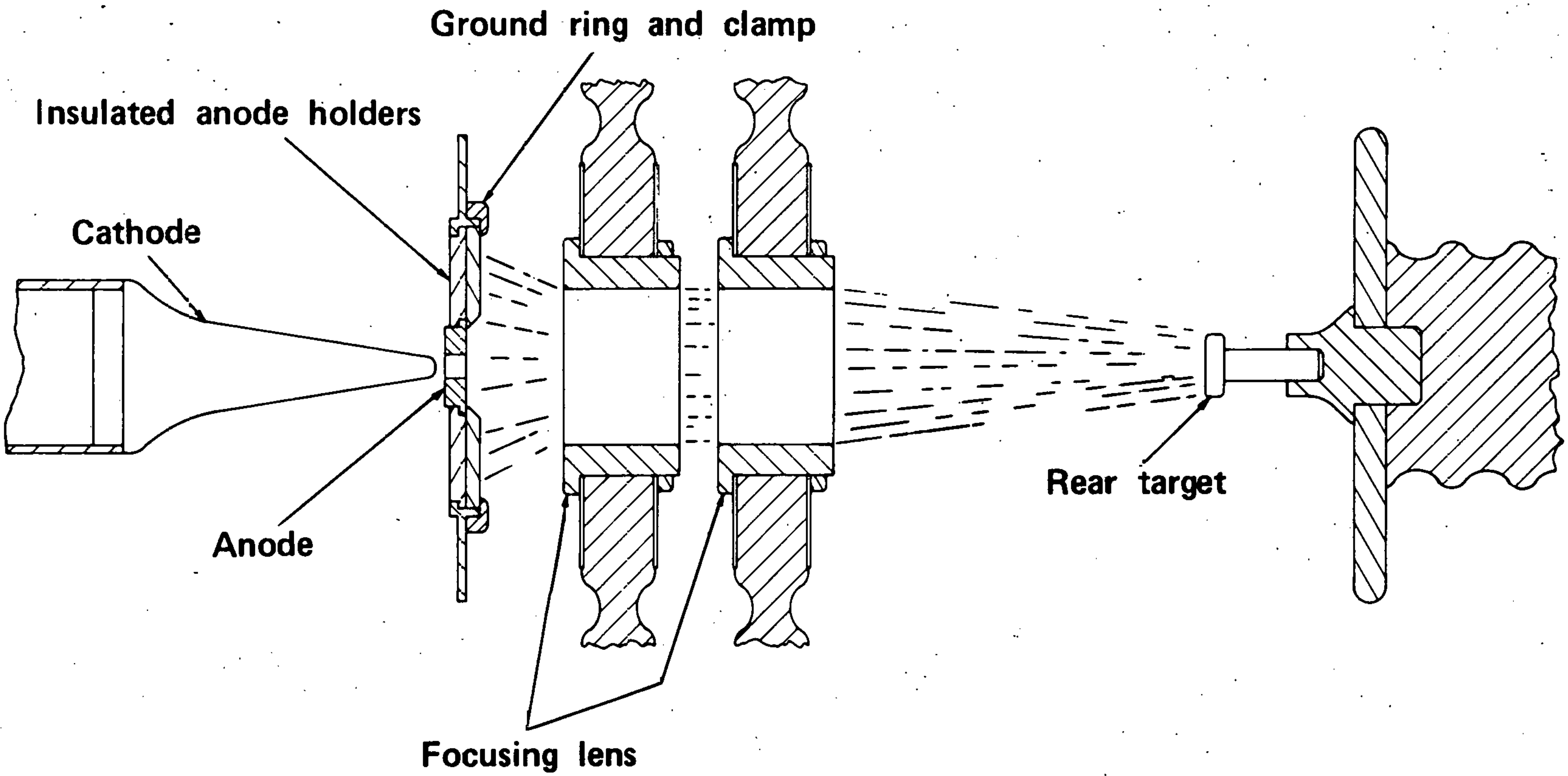


FIGURE 2 DEFOCUSED BEAM

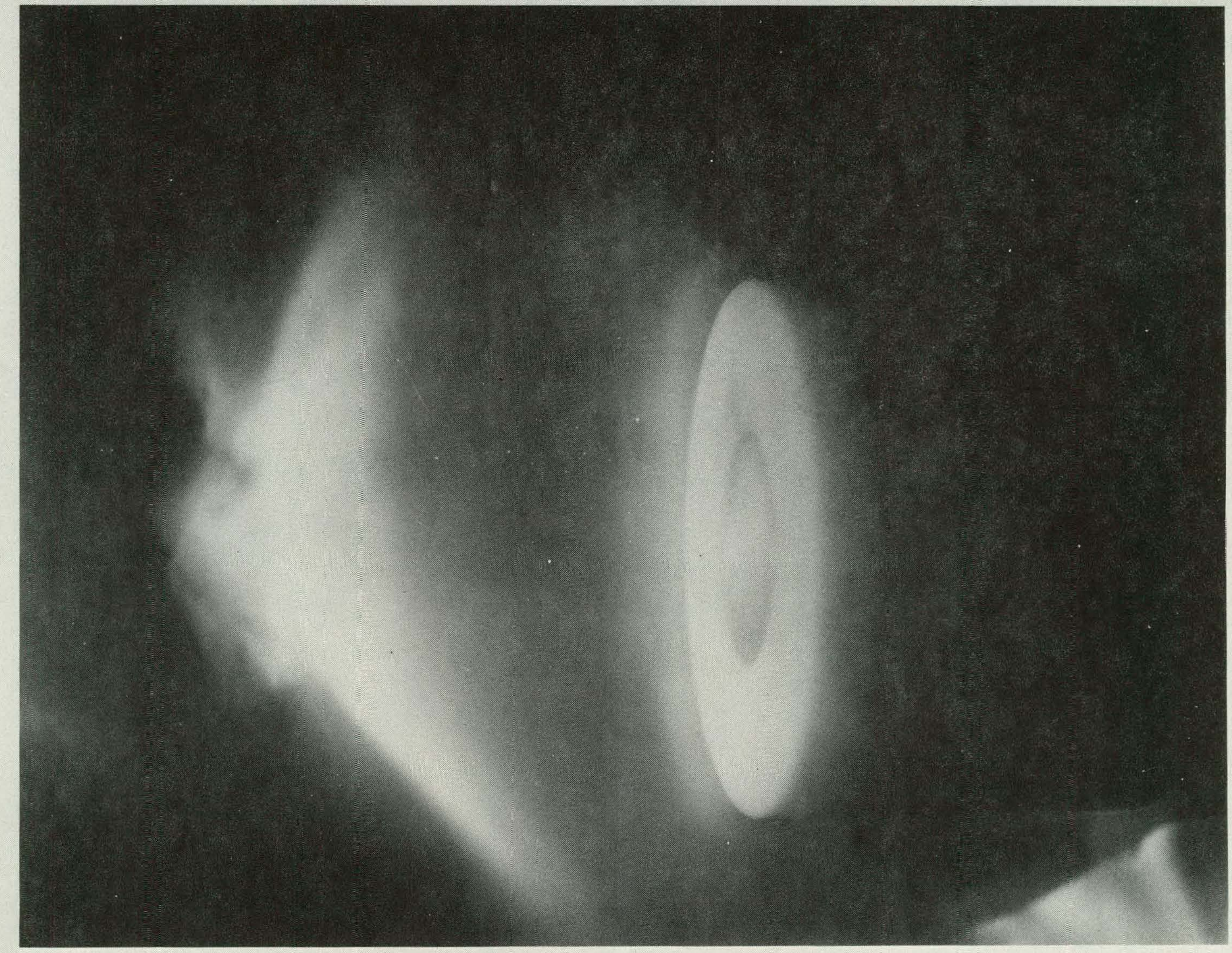


FIGURE 3 FOCUSED BEAM—SINGLE LENS

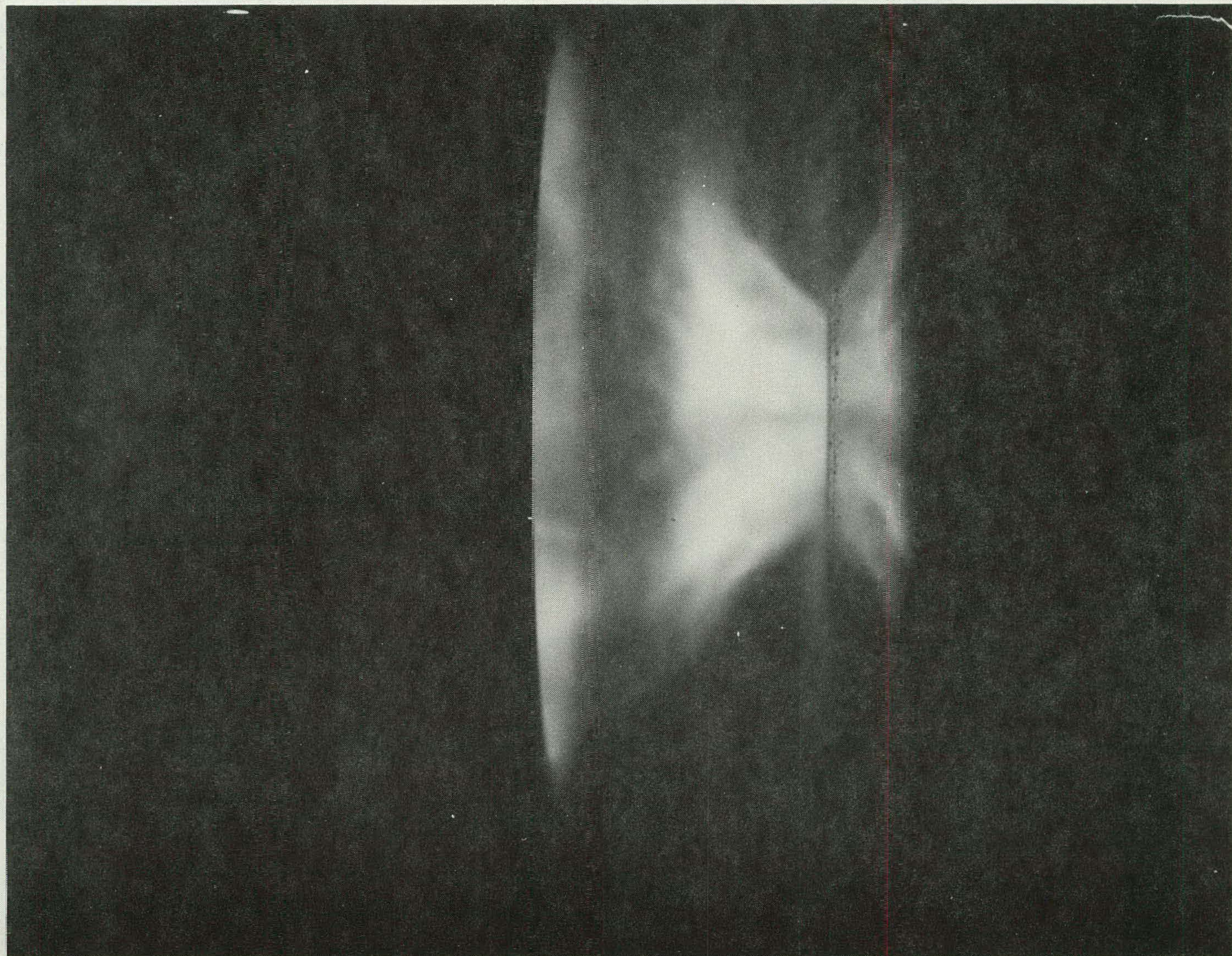


FIGURE 4 THREE STAGE LENS

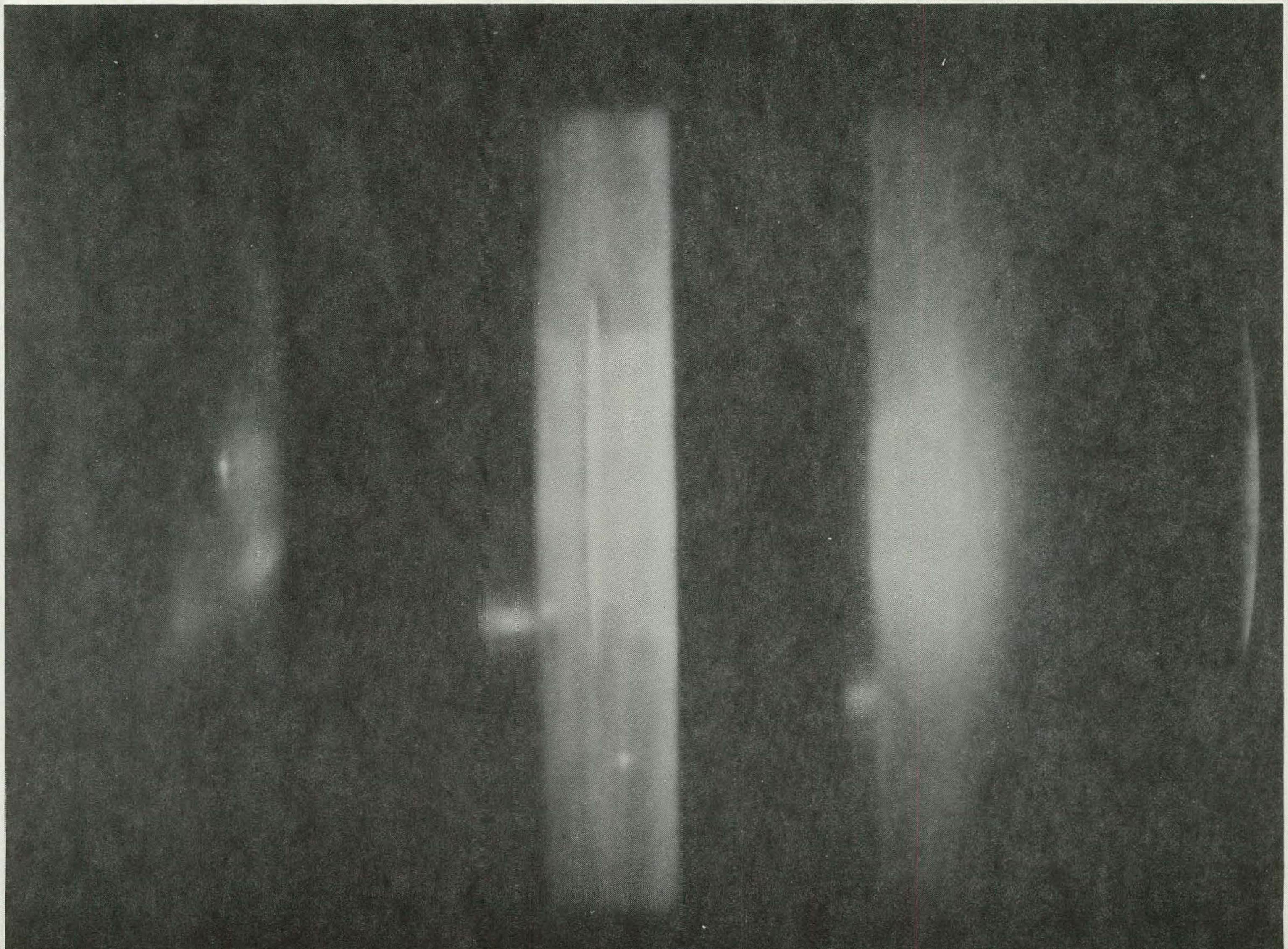


FIGURE 5 RANDOM VORTEX FILAMENTS

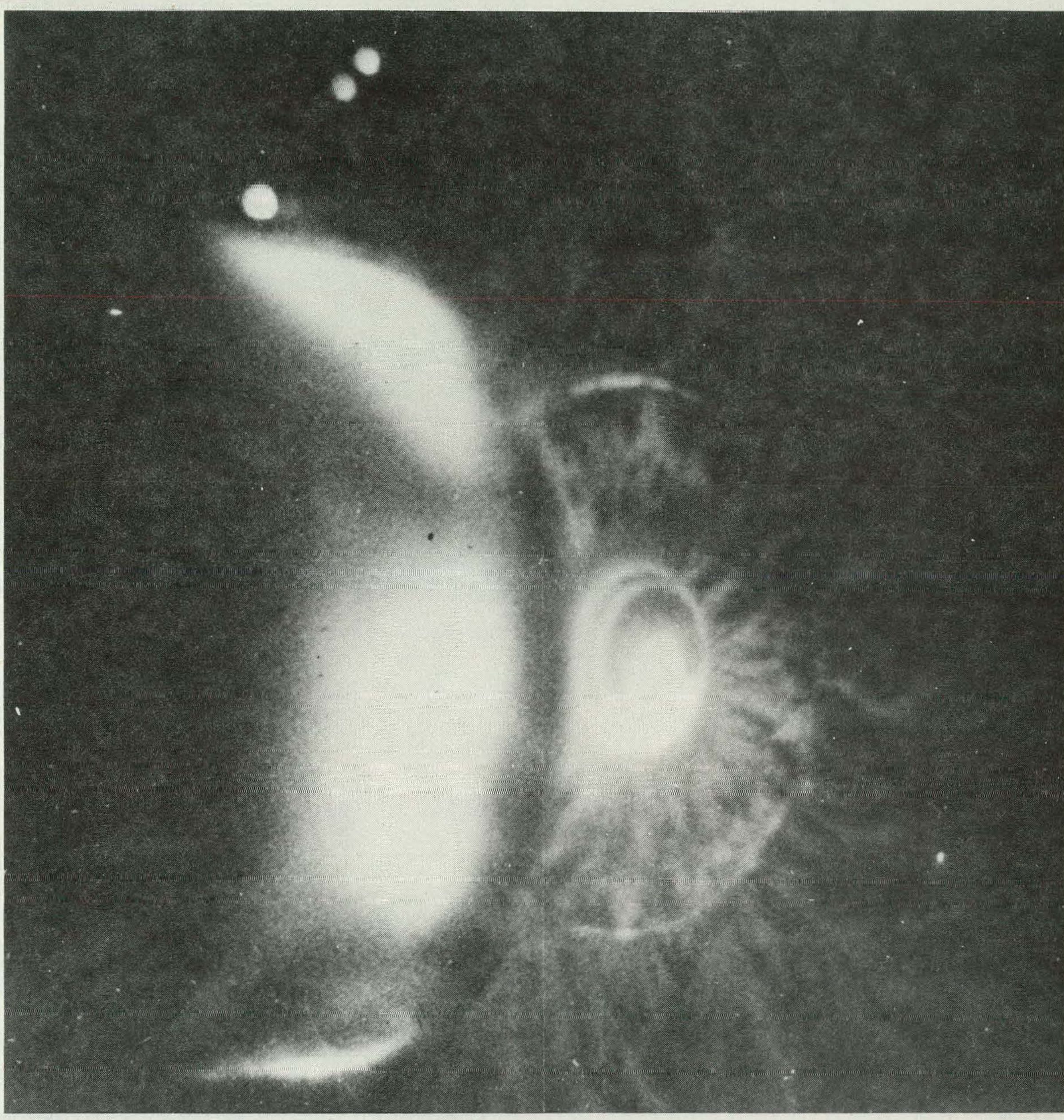


FIGURE 6 VORTEX FILAMENT MARKINGS TARGET SHIELD

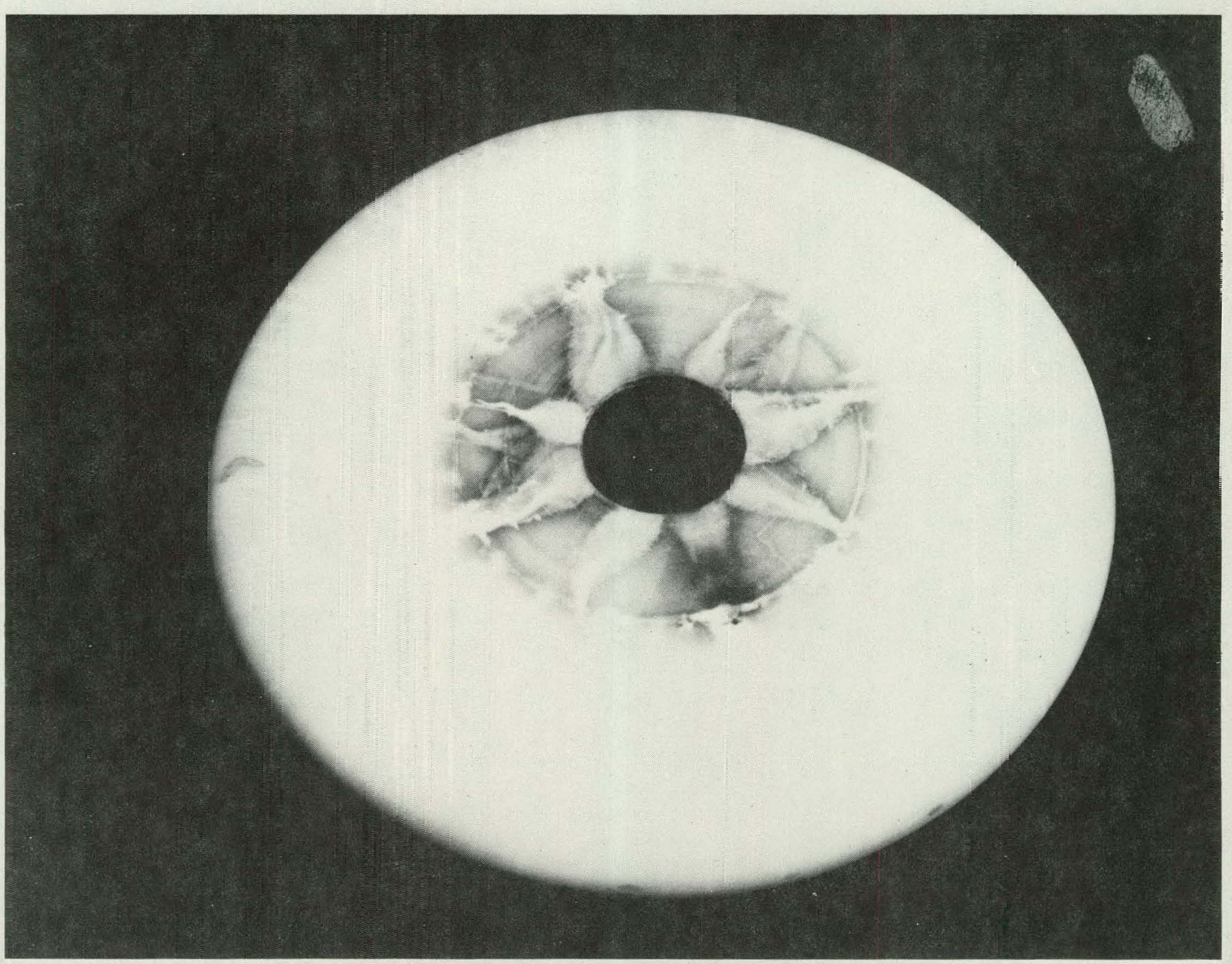


FIGURE 7 INSULATED TARGET ASSEMBLY

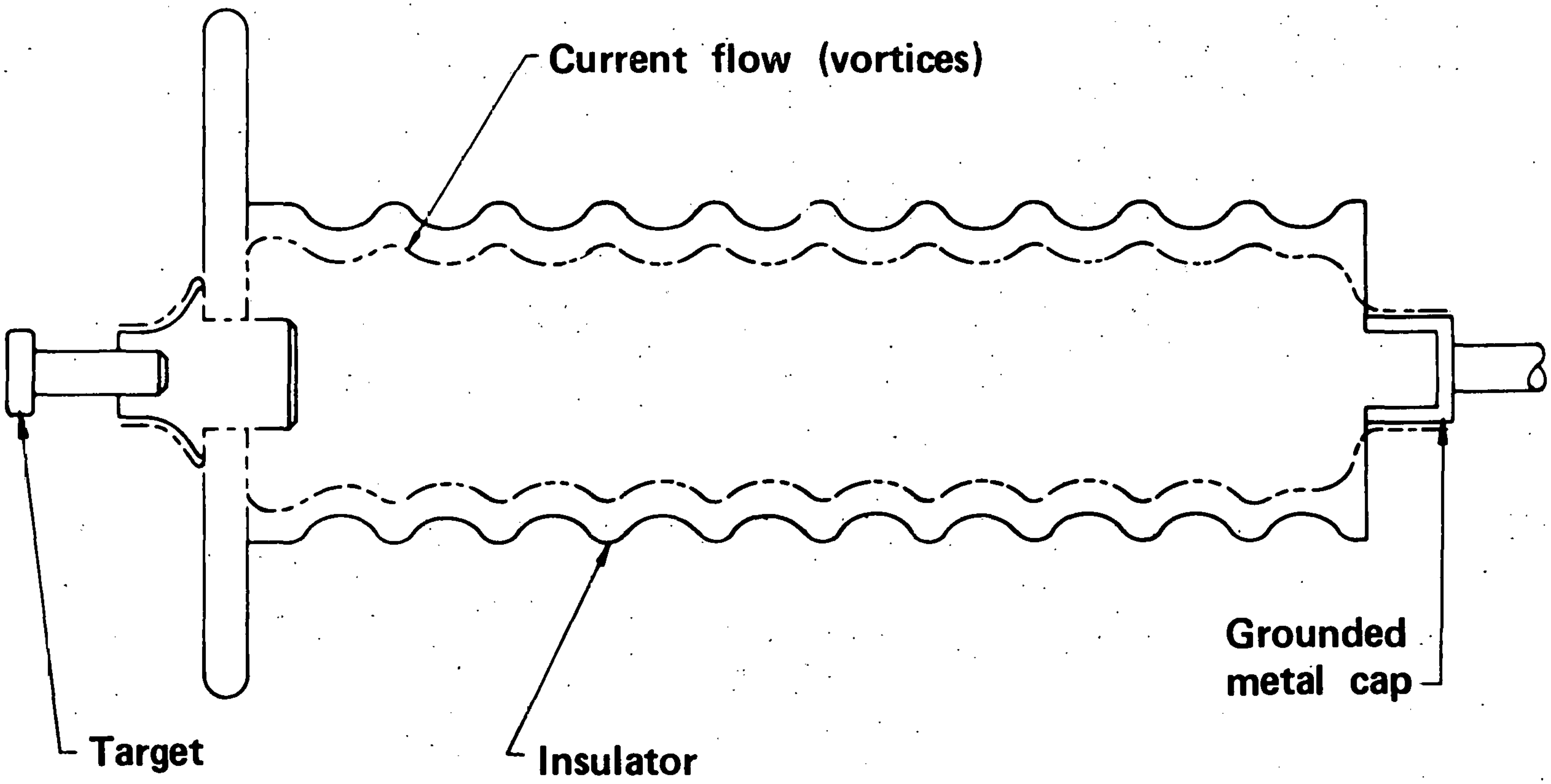


FIGURE 8 PAIR CONFIGURATION—
VORTEX FILAMENTS

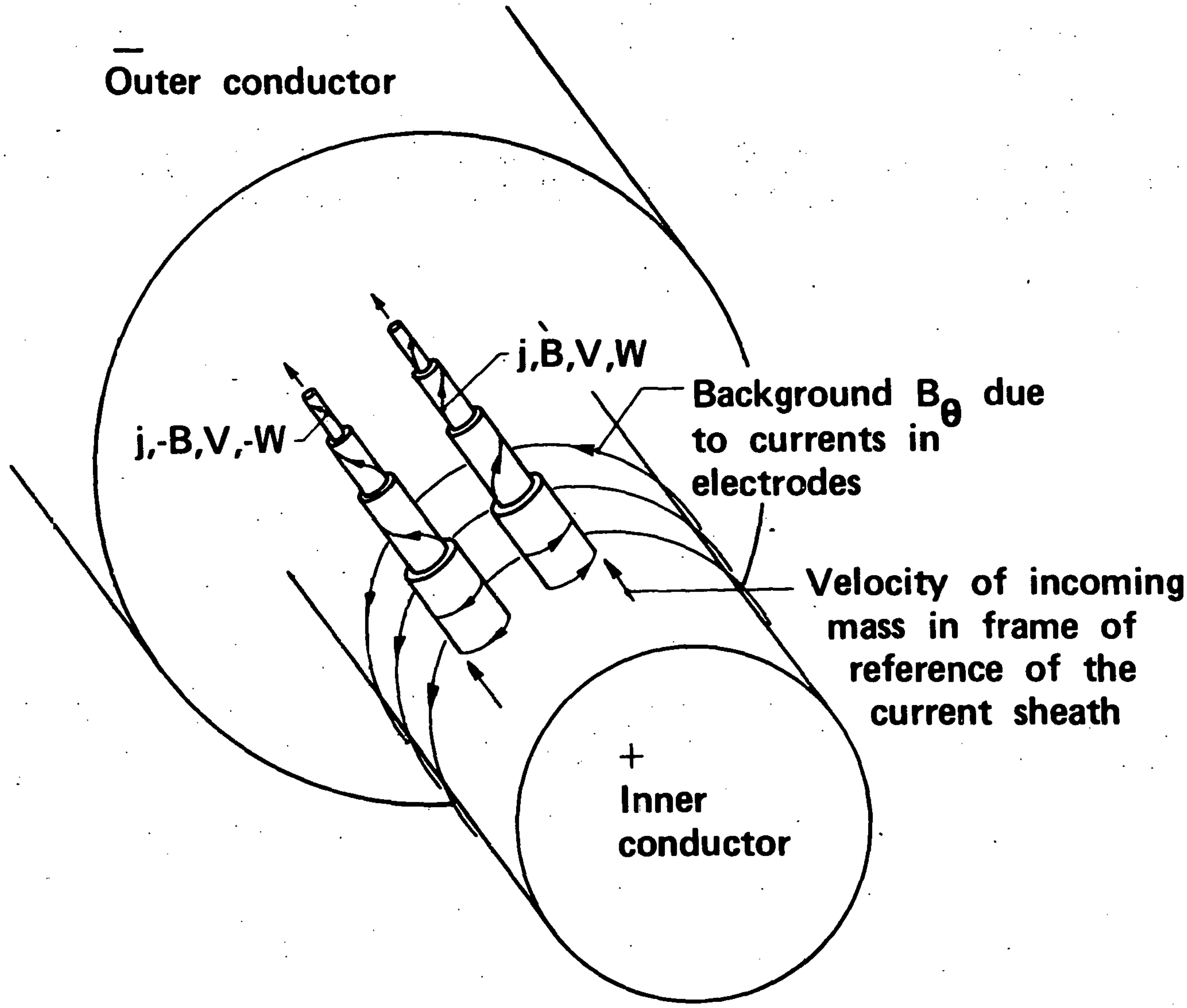


FIGURE 9 PROPAGATION OF VORTEX FILAMENT

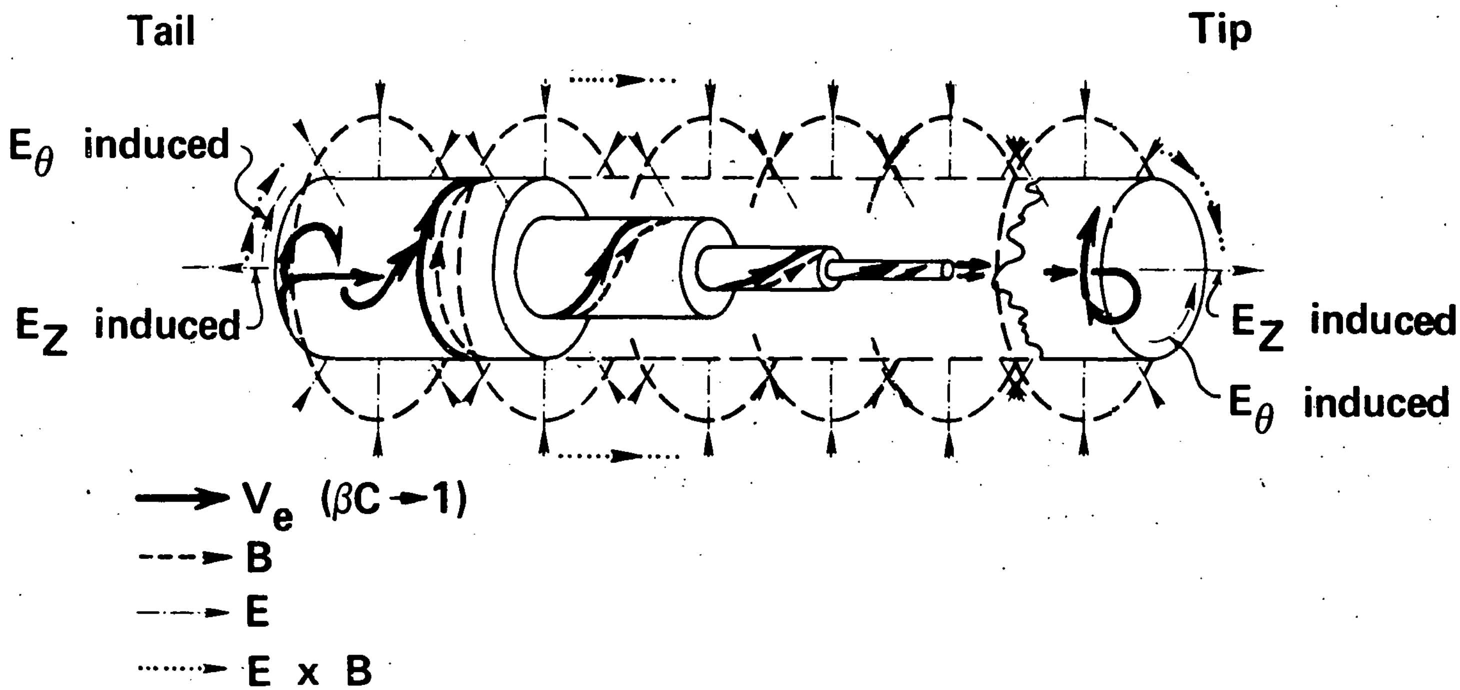


FIGURE 10 COMPOUND CFA ASSEMBLY

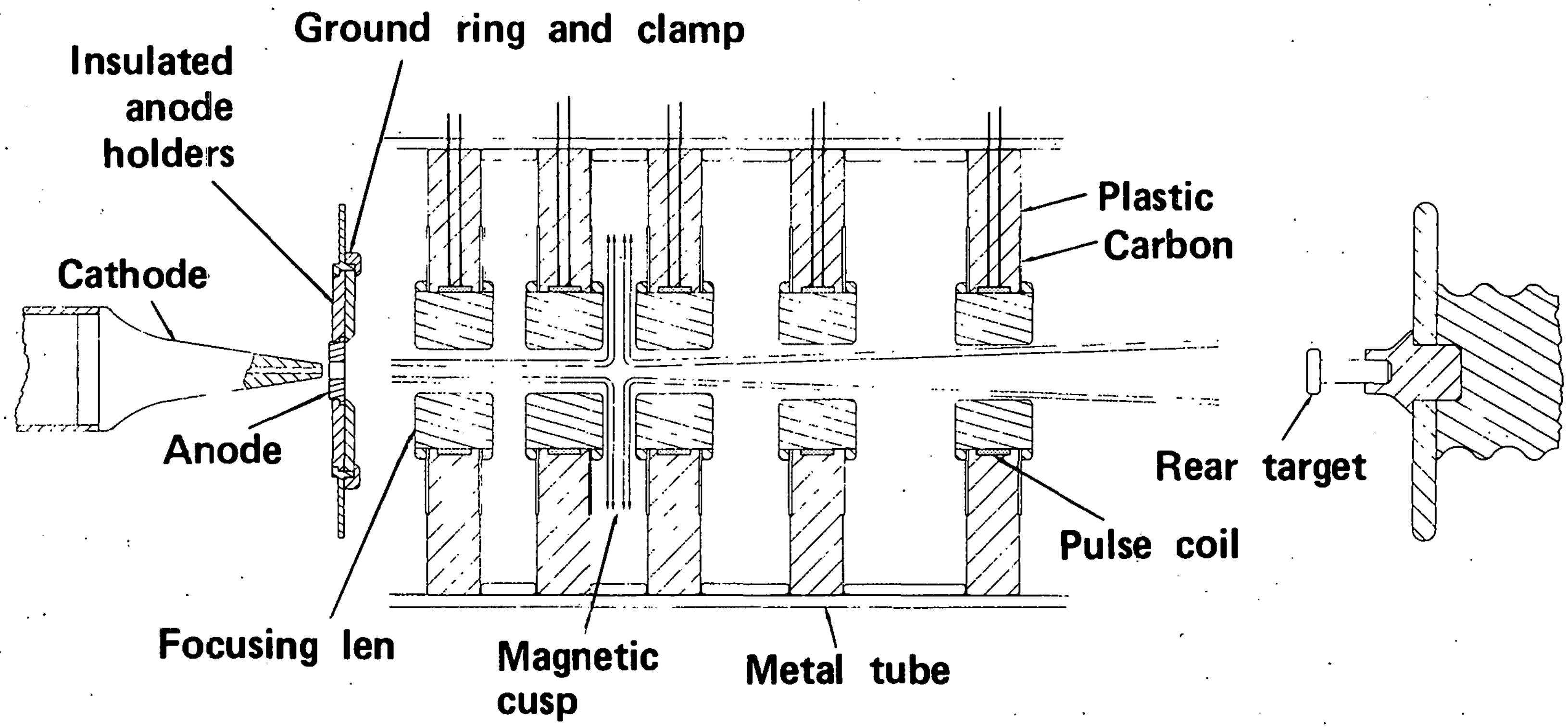
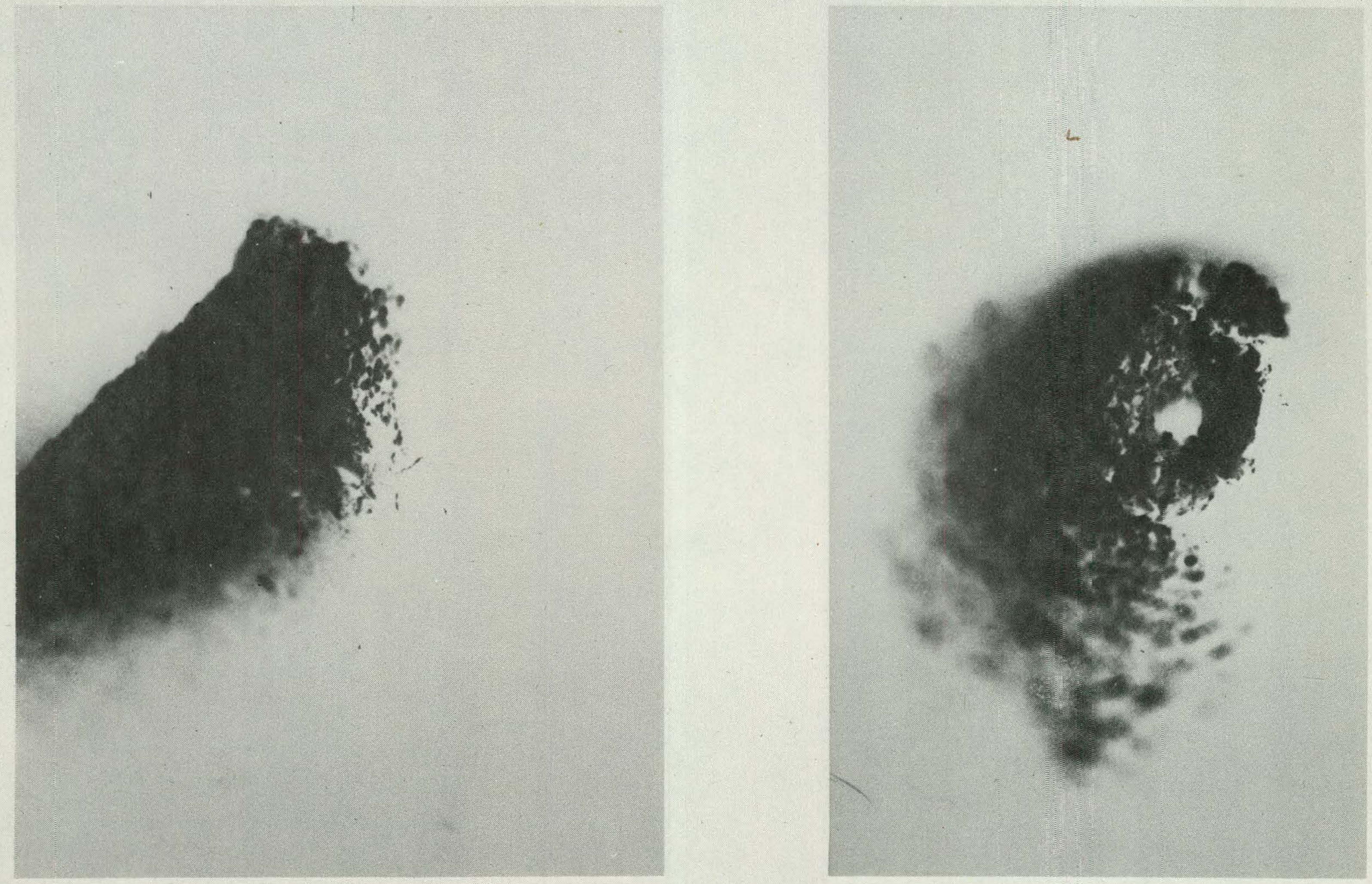


FIGURE 11 HOLE PRODUCED IN COPPER
WITH COLLECTIVE BEAM SINGLE SHOT



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