Enhanced Stability and Neutron Production in a Dense Z-Pinch Plasma Formed from a Frozen Deuterium Fiber

J. D. Sethian, A. E. Robson, K. A. Gerber, and A. W. DeSilva
U. S. Naval Research Laboratory, Washington, D. C. 20375
(Received 5 January 1987)

We have formed dense Z pinches from frozen deuterium fibers ranging in diameter from 80 to 125 μm and at peak currents of up to 640 kA. The pinch remains stable for the entire 130 nsec of the current rise. This anomalously long stable period corresponds to about 100 magnetohydrodynamic growth times. As soon as the current peaks, i.e., when $dI/dt=0$, the pinch goes rapidly $m=0$ unstable and produces nearly 10^{12} neutrons in a 30–60-nsec-wide pulse. The instability occurs only at $dI/dt=0$ and is independent of either the current magnitude or the time to peak.

PACS numbers: 52.55.Ez

As an alternative to the conventional magnetic-confinement approach to fusion, where the plasma density is limited by the strength of an externally applied magnetic field, the linear Z pinch, which is confined solely by its self-field, can in principle confine a much higher-density plasma, and should thus require a correspondingly shorter containment time for net energy production. Because of this, as well as its attractive simplicity, the Z pinch was investigated extensively in the early days of controlled-fusion research. However, all the early experiments were plagued by seemingly intractable magnetohydrodynamic (MHD) instabilities,[1] and the simple Z pinch has long since been abandoned as a candidate for a fusion system. This negative view may need revision in the light of new results from dense Z pinches formed from frozen deuterium fibers, through which rapidly rising currents are driven by means of modern low-impedance pulse generators. This novel formation technique was first proposed in simultaneous articles by Pereira *et al.*[2] and Hammel, Scudder, and Schlachter.[3] The first experiments, with currents up to 250 kA, were reported by Scudder,[4] who found that this type of pinch was stable for many radial Alfvén transit times. We have extended these experiments to higher currents and have found that the pinch is always stable as long as the current is increasing ($dI/dt>0$), and only becomes unstable when the current peaks ($dI/dt=0$).

In our experiment, we produce the fiber[5] by freezing deuterium in a cylinder at 4.2 K, raising it to 11 K where it becomes plastic, and then extruding it through a small orifice into a vacuum system. The chamber pressure is 10^{-4} Torr in the presence of the fiber. The fiber bridges a 5-cm gap between two electrodes to which a voltage of 400–600 kV is applied by the U. S. Naval Research Laboratory POSEIDON pulse generator. This causes the fiber to break down and become a conducting pinch within about 10 nsec. The generator is capable of driving up to 640 kA through the pinch with a rise time of 130 nsec.

In Fig. 1, we show the current wave form and corresponding streak photograph of a pinch formed from a 125-μm-diam fiber. The photo is taken in visible light through a 100-μm slit oriented perpendicular to the pinch axis. By taking streak photographs through dif-

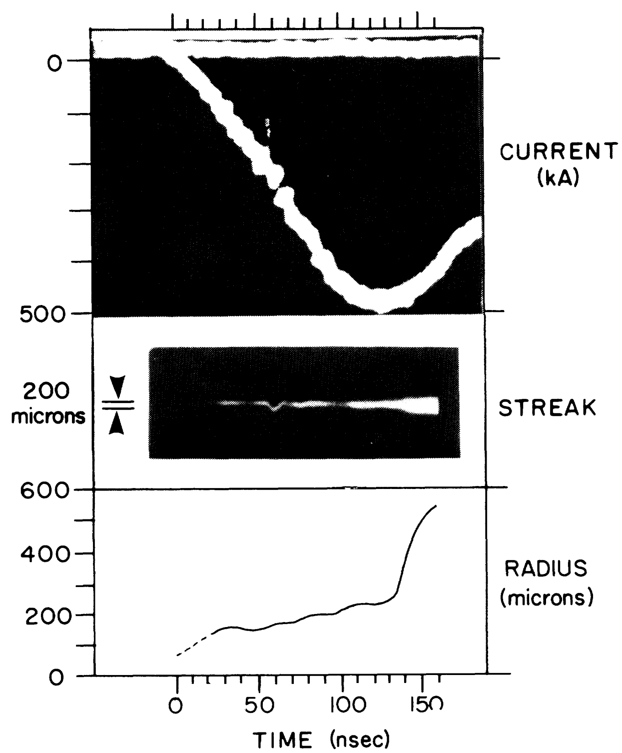

FIG. 1. Pinch current, streak photograph, and plot of $r(t)$. The streak photograph has a deflection imposed on it at about 59 nsec by applying a voltage pulse to the camera deflector plates. This allows synchronization with other diagnostics: Note the corresponding marker on the current trace. The dotted part of the graph has been confirmed by removing neutral density filters from the camera.

Work of the U. S. Government
Not subject to U. S. copyright

ferent neutral density filters we have established that the pinch has a sharp boundary, whose radius versus time is plotted in the lower portion of the figure. This clearly shows the characteristics we will examine in this paper: During the current rise, the pinch expands rather slowly and appears to be quite stable, and when the current peaks, it undergoes a rapid expansion.

We define an Alfvén speed $v_A = I/(10^7 NM)^{1/2}$, where I is the current, N the ion line density, and M the ionic mass in mks units. When we compare this with the radial velocity v_r we find that $v_r \ll v_A$ at all times. We therefore conclude that the pinch is, to a high degree of approximation, in pressure equilibrium with the magnetic field, and that the first 130 nsec of its observed expansion is simply an adjustment of the equilibrium as the pinch is heated by the Ohmic dissipation of the current. The average temperature T is then given by the Bennett relation[6]: $I^2 = (16\pi/\mu_0)NkT$.

We have developed a zero-d code in which we model the pinch as going through a series of successive equilibrium states. The pinch gains energy through Ohmic heating, and adjusts its radius to maintain pressure balance with the magnetic field of the current. A simple model of radiation loss is included. We use an accurate transmission-line model of the generator circuit in which the pinch is represented as a circuit element with time-varying resistance and inductance. If we assume only Spitzer conductivity at the Bennett temperature, the model predicts a rapid initial expansion to a large radius, which is not what we observe. If, on the other hand, we assume that the conductivity is initially several orders of magnitude larger than the Spitzer value, we can reproduce the initial slow expansion. While it is possible that such a conductivity may arise as a result of electron degeneracy in a plasma at near-solid density,[7] it is more likely that a zero-d model is inadequate to describe the early stage of the pinch, when the cold unionized fiber may coexist with the hotter pinch plasma.

In the later stages ($t > 30$ nsec) the circuit model, with the pinch inductance calculated using $r(t)$ from Fig. 1 and the pinch resistance given by Spitzer conductivity, accurately predicts the observed current wave form. When the fiber is replaced with a 3-mm-diam (3000 μm) steel rod the current is both predicted and observed to be some 20% higher and to peak almost 20 nsec earlier. Since the inductance of the pinch (typically 75 nH) varies only logarithmically with radius, this is not an accurate way to measure the radius, but as the results are consistent with the measurement of $r(t)$ from the streak photographs we feel safe in assuming that the pinch current is indeed confined to the visible regions of the streak photo and is not flowing, for example, in a larger-diameter diffuse plasma. We believe that Fig. 1 is a good representation of the gross dynamic behavior of the pinch.

After peak current, the pinch expands much more rapidly than predicted by the model and produces a large burst of neutrons. We determine the neutron-production time, as well as the neutron energy, by placing two time-of-flight detectors (scintillator/photomultipliers) at distances of 1.18 and 6.00 m from the pinch. As shown in Fig. 2(a), the mean neutron energy perpendicular to the pinch is 2.45 ± 0.05 MeV, which corresponds to the D-D reaction. The neutron pulse varies in width from 30 to 60 nsec, but always rises less than 10 nsec. By advancing the signal by the time it takes the neutrons to reach the detector, we can establish that the onset of the neutron pulse always occurs at peak current. To check that this coincidence is not fortuitous, we varied the pinch current by changing the charging voltage on the generator, which also changes dI/dt. We also changed the time to peak by taking advantage of the natural variation in the time the fiber takes to break down. In Fig. 3, we show examples of two extreme cases where the current is changed from 390 to 510 kA, and the time to peak varies from 110 to 130 nsec. In all of these experiments the neutron pulse invariably occurred when $dI/dt = 0$, independent of the current magnitude or time to

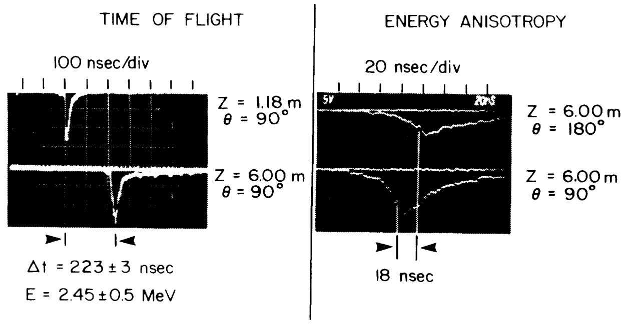

FIG. 2. Neutron energy and energy anisotropy from time-of-flight signals.

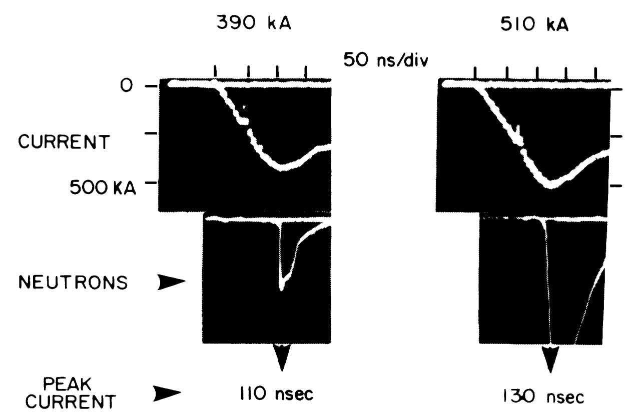

FIG. 3. Onset of neutrons, for two different values of current and time to peak. (The neutron pulse at 510 kA is larger because of the higher current.)

peak.

We measure the number of neutrons with a rhodium-foil activation counter and find the yield to rise rapidly with the pinch current (Fig. 4). Maximum yields to date have been 8.4×10^{11} neutrons at a current of 640 kA. For the shot illustrated in Fig. 1, peak current 500 kA, the yield was 2×10^{11} neutrons. If we calculate the number of D-D reactions expected from a uniform pinch, with $r(t)$ given by Fig. 1 and the temperature given by the Bennett relation, we obtain a value of about 2 neutrons/shot. Furthermore, the dispersion in time of the signal from the farther detector in Fig. 2(a) indicates a temperature of about 40 keV for the reacting deuterons, although the Bennett temperature at this point is only 53 eV. Clearly the neutrons do not come from a uniformly heated plasma. On the other hand, it is well known that a Z pinch can produce a greatly enhanced neutron yield if it becomes unstable.[1]

We have four indications that this is the case in our experiments: First, the neutrons are produced very suddenly in a rapidly rising pulse as soon as $dI/dt=0$. Second, a rapid expansion is seen on the streak photograph at that time. Third, we find from neutron time-of-flight measurements that the deuteron center of mass has a directed motion towards the cathode, as has been observed[1] in other unstable pinches: In Fig. 2(b) we show the signals from two detectors located 6 m from the pinch, one at $\Theta=180°$ (looking counter to the deuteron current), and the other at $\Theta=90°$. The two detectors give similar signals, but the signal from the detector at 180° is delayed by 18 nsec with respect to the detector at 90°. This indicates that the average deuteron center of mass is moving towards the cathode with an energy of 18 keV. (Note that this is still smaller than the thermal energy of the reacting deuterons.) Fourth, x-ray pinhole photographs, taken through a 12.7-μm-thick Be filter, show a straight beaded structure, with the diameter of the "beads" less than 340 μm, the resolution of the pinhole. We typically observe 8 to 10 beads randomly spaced along the length of the pinch.

Figure 5 shows an x-ray pinhole photograph which is unusual in that the fiber was initially curved, which did not seem to affect the pinch. A p-i-n diode with an

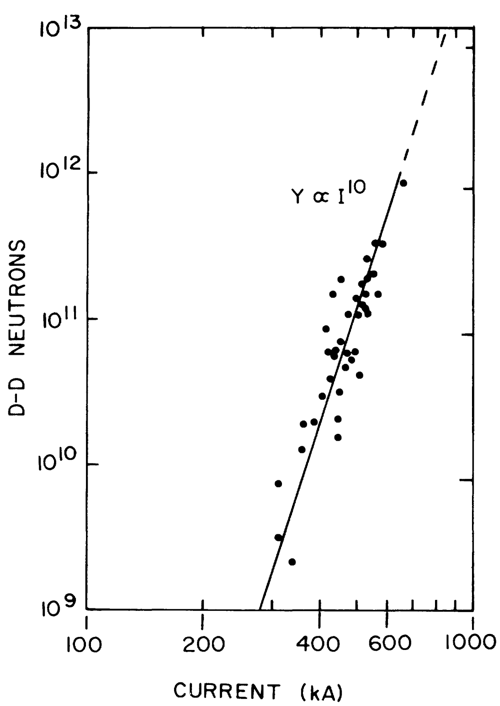

FIG. 4. Neutron yield as a function of current. Fiber diameter, 80 μm. The yield is well represented by the expression $Y=7.3\times10^{13}\,I^{10}$ (I in MA).

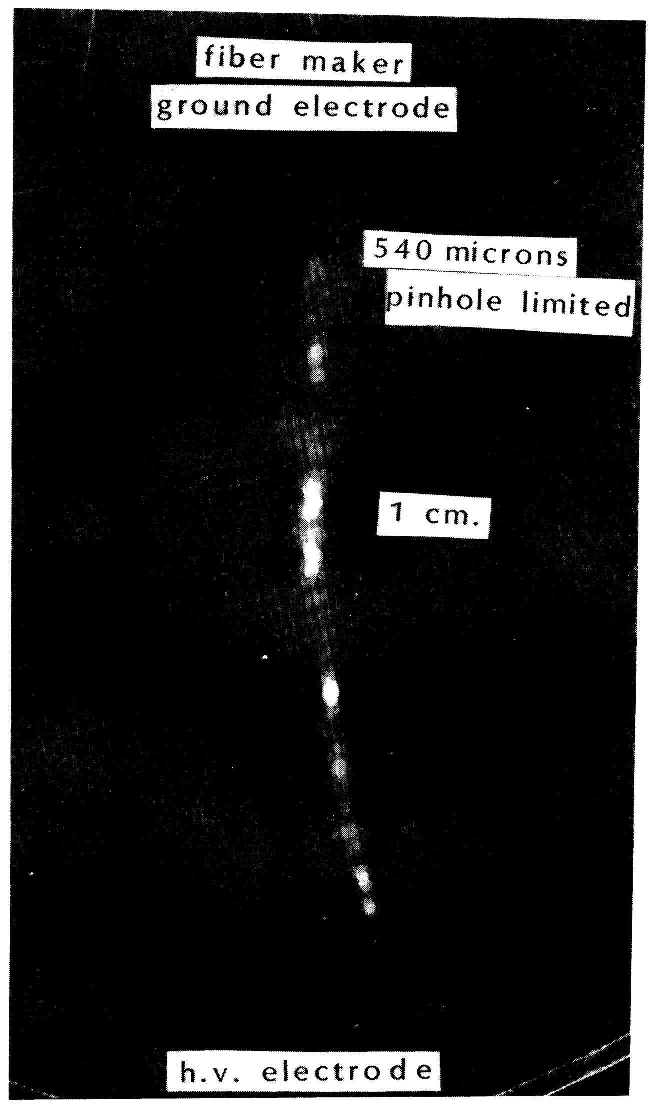

FIG. 5. X-ray pinhole photograph. The pinch current was 350 kA.

identical Be filter shows a burst of x rays at the same time as the neutron pulse. Measurements with different filters indicate that these are soft x rays (<300 eV). Since no other x-ray signals are seen, we conclude that the pinhole photographs are exposed at peak current at the same time the neutrons are produced. All these observations are indicative of an $m=0$ instability occurring at peak current and leading to localized regions of very high density and temperature. The remarkable neutron yield, and the even more remarkable scaling with current, will be the subject of a future paper. For the present, the significance of the neutrons is that they provide an accurate indication of when the pinch becomes unstable. We find this always occurs at peak current, when $dI/dt=0$, and so we conclude the pinch must be stable up to that point.

In light of this behavior, the immediate question is why the pinch is stable for so long: From ideal MHD theory, both $m=0$ and $m=1$ modes are predicted to grow with wavelengths on the order of the pinch radius a, and with linear growth rates $\gamma \simeq v_A/a$.[8] Using the data in Fig. 1, at peak current we find $1/\gamma \simeq 2$ nsec, which is consistent with the rise time of the neutron signal. However, up to that time $\int \gamma dt \simeq 40$, yet no instability is seen. The longest stable period we have observed, for an 80-μm fiber pinch carrying 640 kA, corresponds to 100 Alfvén transit times. These observations are obviously inconsistent with the predictions of MHD theory and we need to look for features of the experiment that are not included in the assumptions upon which the theory is based. The MHD models usually assume uniform temperature and uniform current density, which leads to a parabolic profile for the density. Since the density goes to zero at the pinch boundary, the electron drift velocity there would have to have an infinite value. In reality, the electron drift velocity will be limited by microinstabilities to a value comparable to the ion sound speed. This means that there may be a region at the boundary of the pinch where the plasma is not in equilibrium but is expanding at thermal speed; although only a very small fraction of the total particle inventory may be involved (too small to be observed by our diagnostics), the reaction of the expanding plasma upon the main body of the pinch may be sufficient to create an additional stabilizing force that is not considered in the usual theory. When the current reaches its peak, the axial electric field on the pinch reverses direction, as does the current in the outer region of the pinch (the inverse skin effect[9]). The coronal layer will now be repelled electromagnetically from the pinch, and whatever influence it had on the stability will be lost. This explanation is, of course, very tentative, and resolution of the mystery of the anomalously stable pinch awaits the development of a detailed theoretical model of the experimental situation.

In summary, our experiments demonstrate that a simple high-density linear Z pinch, formed from a frozen deuterium fiber in a vacuum, is stable as long as the current is rising. If these results could be extended to smaller diameter fibers and higher currents, for which the Bennett temperature would be several kiloelectronvolts, or if the neutrons produced by the instability continue to scale favorably with current, we believe that it would be appropriate to reconsider the simple Z pinch as a possible approach to fusion.

The authors are grateful for useful discussions with Dr. S. J. Stephanakis, Dr. F. C. Young, Dr. D. Mosher, Dr. R. J. Commisso, Dr. S. O. Dean, Dr. J. E. Hammel, and Dr. D. W. Scudder. We also appreciate the engineering work of Mr. F. Mora and Mr. M. O. Sy and the competent technical assistance of Mr. D. R. Evenson and Mr. J. P. Piccotta. This work was supported by the U.S. Office of Naval Research and the U.S. Department of Energy, and one of us (A. W. DeS.) was supported in part by the University of Maryland and Sachs-Freeman Associates.

[1]O. A. Anderson, W. R. Baker, S. A. Colgate, J. Ise, and R. V. Pyle, Phys. Rev. **110**, 1375 (1958).

[2]N. R. Pereira, N. Rostoker, J. Riordan, and M. Gersten, in *Proceedings of the First International Conference on Dense Z-Pinches for Fusion,* edited by J. D. Sethian and K. A. Gerber (Naval Research Laboratory, Washington, D.C., 1984), p. 71.

[3]J. E. Hammel, D. W. Scudder, and J. S. Schlachter, in Ref. 2, p. 13.

[4]D. W. Scudder, Bull. Am. Phys. Soc. **30**, 1408 (1985).

[5]J. D. Sethian, K. A. Gerber, and M. O. Sy, Rev. Sci. Instrum. **58**, 536 (1987).

[6]W. H. Bennett, Phys. Rev. **45**, 890 (1934).

[7]Y. T. Lee and R. M. More, Phys. Fluids **27**, 1273 (1984).

[8]R. J. Tayler, Proc. Phys. Soc., London, Sect. B **70**, 31 (1957).

[9]M. G. Haines, Proc. Phys. Soc., London **74**, 576 (1959).

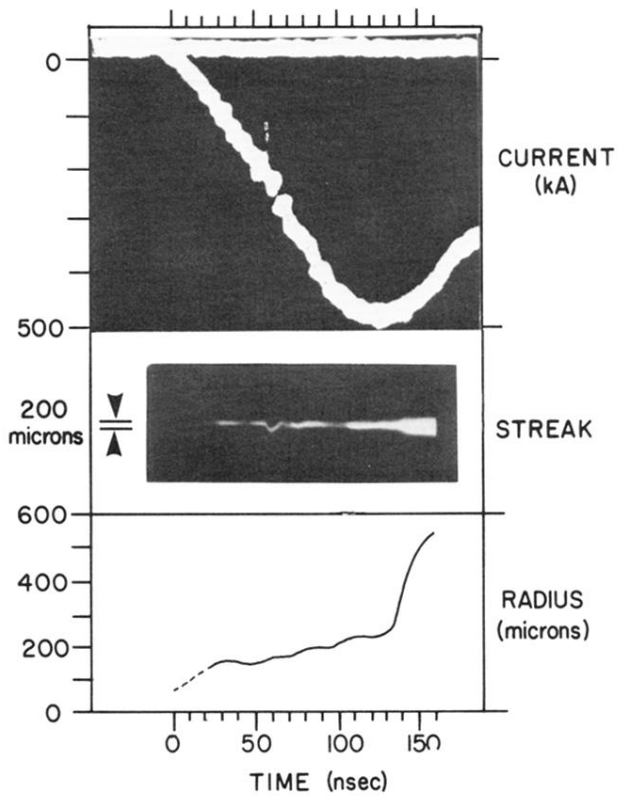

FIG. 1. Pinch current, streak photograph, and plot of $r(t)$. The streak photograph has a deflection imposed on it at about 59 nsec by applying a voltage pulse to the camera deflector plates. This allows synchronization with other diagnostics: Note the corresponding marker on the current trace. The dotted part of the graph has been confirmed by removing neutral density filters from the camera.

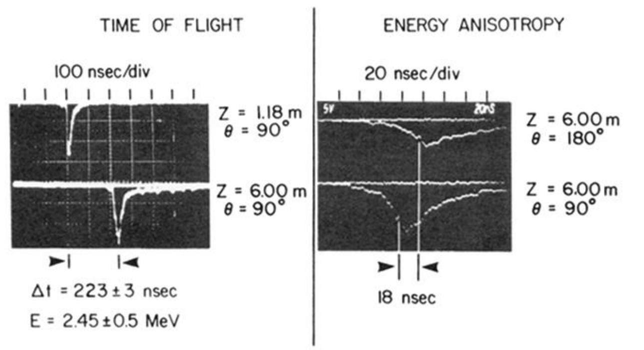

FIG. 2. Neutron energy and energy anisotropy from time-of-flight signals.

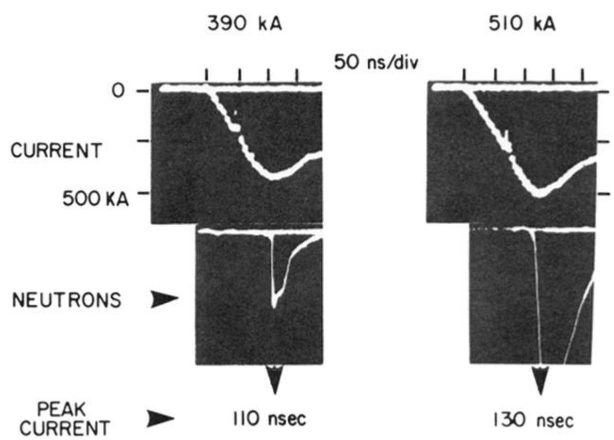

FIG. 3. Onset of neutrons, for two different values of current and time to peak. (The neutron pulse at 510 kA is larger because of the higher current.)

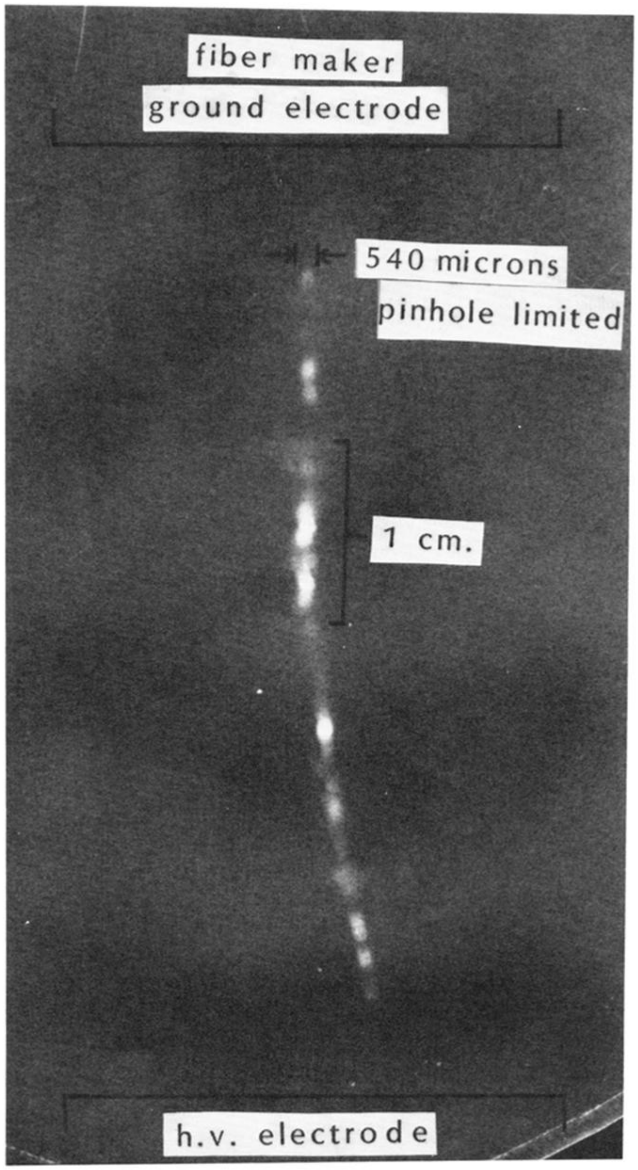

FIG. 5. X-ray pinhole photograph. The pinch current was 350 kA.