# Electron Beam Focusing Using Current-Carrying Plasmas in High-$\nu/\gamma$ Diodes*

G. Yonas, K. R. Prestwich, J. W. Poukey, and J. R. Freeman
*Sandia Laboratories, Albuquerque, New Mexico 87115*
(Received 13 November 1972)

A technique has been demonstrated for concentrating electron beams to $5\times10^6$ A/cm$^2$ plasmas on the axis of diodes. A two-dimensional particle code has been used to illustrate the importance of both the $\vec{E}\times\vec{B}$ motion in vacuum and the self-pinch of the beam within the plasma.

Interest has increased recently in applying intense electron beams to the problem of pulsed fusion. One of the fundamental requirements in achieving such a goal is the focusing of multimegampere currents onto submillimeter targets. For the last five years or more, fairly extensive beam research has been carried out in propagation and compression of 50–500-kA beams beyond the diode, with current densities of $\lesssim 10^5$ A/cm$^2$ achieved. Theoretical and experimental studies have indicated the futility of such an approach insofar as the necessary current densities in the $10^9$–$10^{10}$ A/cm$^2$ range are concerned. The goal of the work described here is to utilize the combined effects of azimuthal magnetic fields together with the applied electric field within the beam-generating diode to accomplish the desired results. We will discuss in this paper experimental and computational results giving the properties of self-pinched beams in diodes, and the focusing improvement obtained as a result of placing a current-carrying plasma along the diode axis.

It was observed in early experiments with high-$\nu/\gamma$ diodes that when a critical value of the current was reached, self-pinching of the beam occurred. Although the resultant current density at the anode ($\sim 10^5$ A/cm$^2$) was in excess of the space-charge–limited value, the pinch was not reproducible and formed late in the pulse with a radial collapse velocity of $\sim 0.1$ cm/nsec. Ecker[1] found that impedance values could be correlated at current maximum with a "parapotential" model originated by De Packh.[2] This model treated the electron trajectories as lying along conical equipotentials with an arbitrarily imposed current along the axis, and it did not treat motion across equipotentials at the cathode edge nor at the anode.

Recent numerical studies of this problem[3] have shown that although the dominant mechanism in such a self-pinched diode is $\vec{E}\times\vec{B}$ motion toward the axis, the assumptions of the parapotential model do not apply. These calculations show that a substantial concentration of current will occur on axis of such a diode if a layer of plasma exists near the anode. They also show that the $\nabla B$ drift away from the anode, as well as space charge near the axis, will tend to inhibit the pinch formation. The primary effect of the space-charge buildup is to distort the equipotentials sufficiently to force electrons into the anode before they reach the diode axis. Experiments have been conducted to minimize both of these detrimental effects in order to further enhance the diode self-pinch.

Mosher *et al.*[4] showed that exploding wires could be used in low-impedance diodes to achieve output loads in the 1-Ω range, and that under certain circumstances an energetic beam could be generated within such a wire. After we noted that in Mosher's experiment the energetic beam component could have originated at the wire holder and accelerated part way across the gap before being focused by the conduction current in the wire, experiments to enhance the conventional diode self-pinch using such a focusing effect were carried out.

The present experiments were conducted with a 200-kV, 100-kA, 30-nsec water coaxial pulser, Nereus, and a 250-kV, 250-kA, 100-nsec Mylar-strip line pulser, Slim. The diode configuration used on Nereus consisted of a conventional 5.08-cm-diam Aquadag-coated cathode with a recessed central region. This type of cathode permitted the use of a wire of sufficient length (3.2 cm) to achieve a wire impedance comparable to that of the normal diode without the wire. A similar configuration on Slim using a 17.8-cm-diam cathode is shown in Fig. 1, where we note the Faraday cup used to determine the conduction current in the wire and the energetic beam current extracted through the anode.

Figure 2 shows aluminum witness plates used as anodes on Nereus and indicates that little energy is delivered to the anode when only the wire itself is used as the output load. The diode impe-

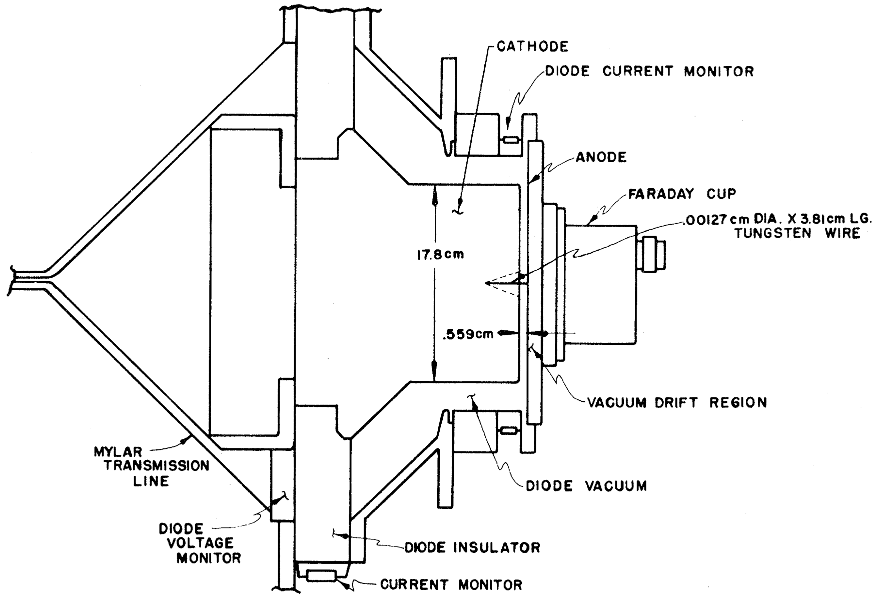
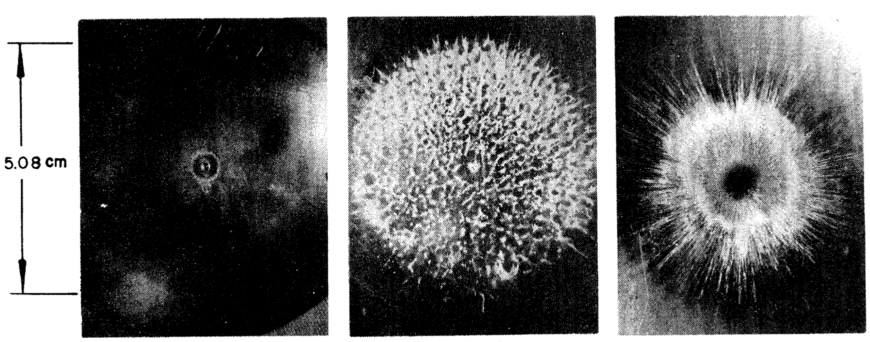



FIG. 1. 250-kV, 250-kA diode configuration.

dance measured without the wire and an anode-cathode gap of 0.381 cm was found to be 3 Ω with no evidence of diode pinching. This is in agreement with space-charge-limited current which is close to the critical pinch value. On the other hand, with the wire inserted in the diode, the diode impedance (excluding the wire current) increased from 3 to 8 Ω and the beam was observed to pinch tightly into the central spot [Fig. (2c)]. Note the extensive front-surface blowoff of molten aluminum shown emanating from the central crater, indicating considerably higher energy densities than in the other two cases. In spite of this gross indication of high energy densities, no anode debris was found on the cathode, which may be an indication of substantial magnetic confinement of the blowoff. Faraday-cup measurements were made with apertures in 0.254-cm-thick Mylar sheets placed in front of the Faraday cup. Monte Carlo calculations were carried out to show that, at most, 2% of the beam would penetrate this thickness. The size of this aperture was varied, indicating that the current-carrying wire effectively focused the current emitted by the cathode into the central $10^{-2}$ cm$^2$ with current densities of approximately $3\times10^6$ A/cm$^2$.

Using Slim as shown in Fig. 1, but without a wire on axis, only slight pinching was observed with current densities of at most 10 kA/cm$^2$ and a diode impedance of 1.0 Ω. Using a 3.2-cm-long wire with a measured impedance of 1.6 Ω during




(A) (B) (C)

FIG. 2. Aluminum witness plates showing relative beam concentration. (a) Wire only; (b) cathode only; (c) cathode with wire.

the pulse, a cathode impedance of 3.0 Ω and strong beam concentration was observed. X-ray pinhole photographs and carbon witness plates were used to determine the radial distribution of current density. It was noted that the front surface crater had a maximum diameter of 0.6 cm, was an order of magnitude deeper than previously observed with self-pinched beams, and was 3 times deeper than the maximum range of the most energetic electrons. The pinhole photographs showed that 93% of the current was contained within a radius of 0.2 cm. The pinhole resolution was ~ $10^{-3}$ cm$^2$, with 7% of the current within that area, and a peak indicated current density of $5 \times 10^6$ A/cm$^2$.

Numerical experiments using a two-dimensional (2D) particle code which simulated the Nereus case show that the dominant electron emission is from the outer portion of the cathode area, and most of the cathode current emitted from this area enters the wire and is focused onto the anode. Typical electron trajectories are shown in Fig. 3. We also note that the magnetic field from the wire current tends to suppress cathode emission near the axis, explaining the increased diode impedance.

After the electrons from the surface of the cathode approach the exploded wire, they pass through the surface of the plasma where they find themselves to be part of a charge-neutral, large-$\nu/\gamma$ beam being accelerated toward the anode. It was necessary to assume that the wire had expanded to a radius of ~0.4 cm in order to allow the energetic electrons to enter the wire plasma without first striking the anode. This assumption of an expanded wire plasma is reasonable in view of the 4-kV, 500-nsec prepulse which is adequate to pre-explode the wire. The experimental results indicate an enhanced focusing of the charge-neutral, high-$\nu/\gamma$ beam after the electrons enter the wire channel. One possible explanation for this effect is provided by solving the "Alfvén problem" with the addition of the diode accelerating field $E_z$. The solution for this problem, obtained by modifying a code developed previously,[5] is shown in Fig. 4(a), where an initially cold beam was assumed. We have verified that a comparable degree of pinching is obtained if one starts with more realistic initial condi-

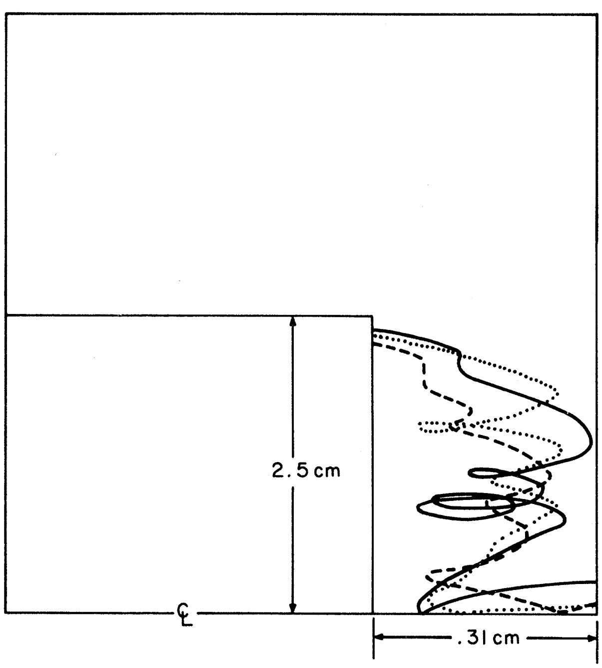



FIG. 3. Typical electron trajectories in a 200-kV, 100-kA diode.

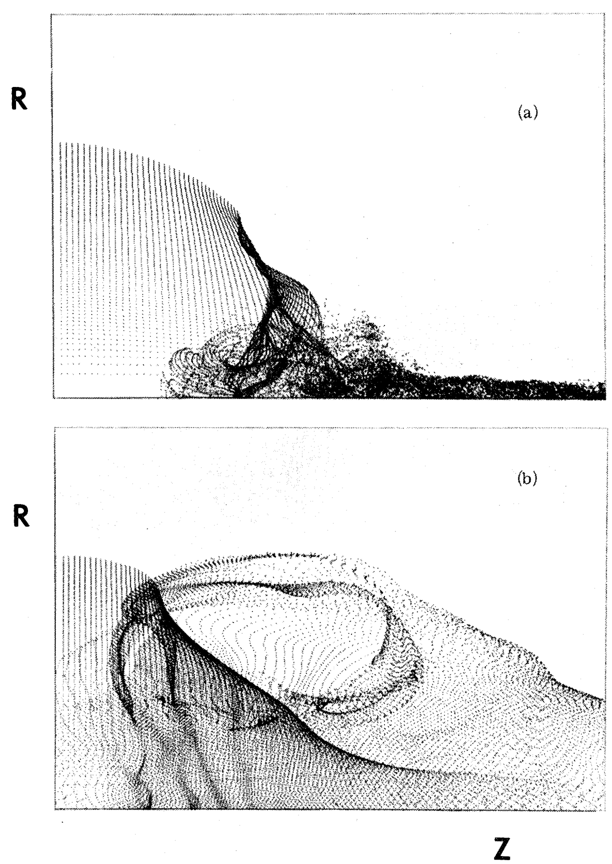



FIG. 4. (a) Electron distribution for a charge-neutral, $\nu/\gamma$=2.8 beam within the wire plasma, showing the effect of self $B_\theta$ and applied $E_z$. (b) Electron distribution for case (a) without $E_z$ (axial scale is about twice radial scale).

tions, e.g., the electrons enter the wire from above with a thermal velocity spread. Repeating the calculation of Fig. 4(a), but without a longitudinal $E_z$ results in poor propagation and little concentration, as shown in Fig. 4(b). We therefore see that the wire plays two important functions. The first is to define a sufficiently large $B_\theta$ field to allow the $\vec{E}\times\vec{B}$ motion toward the wire, and the second is to provide sufficient space-charge neutralization near the axis so that the fields within the wire can further focus the flow without being inhibited by space-charge repulsion.

A technique has been demonstrated for concentrating high-current energetic beams using exploding wires on the axis of high-$\nu/\gamma$ diodes. Experiments have shown that current densities approximately $5\times10^6$ A/cm$^2$ have been achieved and a 2D particle code has illustrated the importance of both the $\vec{E}\times\vec{B}$ motion toward the wire and the self-pinch of the beam within the plasma. The addition of a longitudinal electric field to the flow of a charge-neutralized beam within the wire allows the beam to propagate in a stable self-pinched, high-$\nu/\gamma$ configuration. It is speculated that such a technique could be employed in a single, megavolt, multimegampere diode to achieve beam conditions needed for pulsed fusion feasibility studies.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]B. Ecker, Bull. Amer. Phys. Soc. 16, 1249 (1971).
[2]D. De Packh, Naval Research Laboratory, Radiation Progress Internal Report No. 7, 1968 (unpublished).
[3]J. Poukey, J. Freeman, and G. Yonas, Bull. Amer. Phys. Soc. 17, 981 (1972).
[4]D. Mosher *et al.*, Bull. Amer. Phys. Soc. 16, 1227 (1971).
[5]J. W. Poukey *et al.*, Phys. Rev. Lett. 26, 1620 (1971).

# Tunneling Observation of Bound States in a Normal Metal–Superconductor Sandwich

J. M. Rowell
*Bell Laboratories, Murray Hill, New Jersey 07974*
(Received 4 December 1972)

Bound states in the pair potential well produced in a normal metal by contact with a superconductor have been observed by tunneling in Pb/Zn-zinc oxide-Pb junctions.

If a thick normal metal and a superconductor are brought into contact, the pair potential in the superconductor can be regarded as a potential barrier for single-particle excitations in the normal metal as long as their energy is less than the superconducting energy gap ($\epsilon$). For such a system, de Gennes and Saint-James[1] calculated the excitation spectrum in the $N$ layer and predicted the existence of bound states within this potential well, the level spacing depending on the inverse thickness of normal metal. Virtual levels produced at energies $>\epsilon$ by the same discontinuity in pair potential have been observed by tunneling into the $S$ layer by Tomasch[2] and into the $N$ layer by the author and McMillan.[3] Reported here is the tunneling observation of bound levels in thick zinc films backed by lead, the effects being so strong as to be easily observed in the junction $I$-$V$ characteristics. Temperature and magnetic field dependences of the effect lead to the conclusion that a finite pair potential, induced by the proximity of the Pb, exists throughout the Zn at least up to 4.2 K for Zn film thickness used so far ($\sim 5\,\mu$m). Therefore the observation is actually of bound levels in a superconductor with a small induced energy gap rather than in a normal metal.[4] At energies $>\epsilon$ it will be shown that the amplitude and period of the virtual levels gives direct information concerning the energy dependence of the mean free path and velocity of electrons in zinc.

The bound levels in the superconducting pair potential well, and the virtual levels above the well, are the result of the unique quasiparticle reflections at the discontinuity of the potential which have been discussed in detail by Andreev.[5] Consider first a superconducting film backed by normal metal, having an abrupt drop in pair potential at the interface and an excitation spectrum as sketched in the insets of Fig. 1. As the quasiparticle states at $k_1$ and $k_2$ are linear combinations of electron and hole, an electron injected into $S$ at energy $E$ overlaps $\frac{1}{2}[1+E/(E^2+\epsilon^2)^{1/2}]$ with $k_1$ and $\frac{1}{2}[1-E/(E^2+\epsilon^2)^{1/2}]$ with $k_2$. If $S$ is suf-

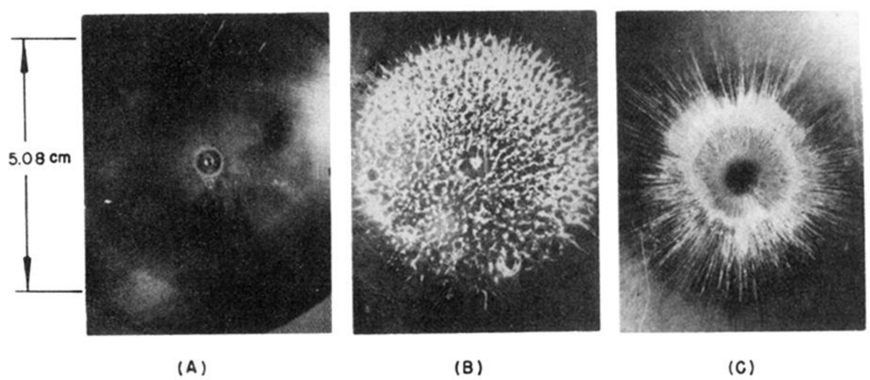



FIG. 2. Aluminum witness plates showing relative beam concentration. (a) Wire only; (b) cathode only; (c) cathode with wire.

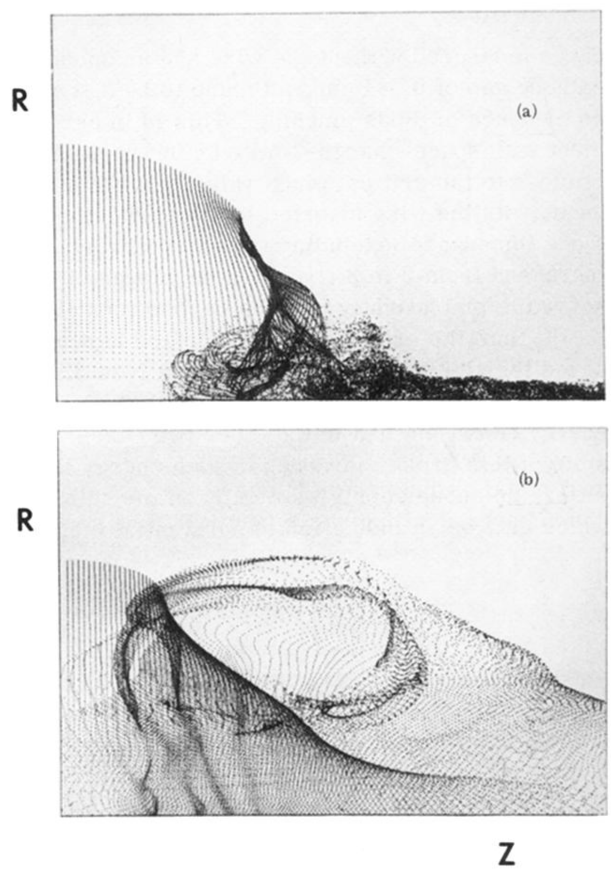



FIG. 4. (a) Electron distribution for a charge-neutral, $\nu/\gamma = 2.8$ beam within the wire plasma, showing the effect of self $B_\theta$ and applied $E_z$. (b) Electron distribution for case (a) without $E_z$ (axial scale is about twice radial scale).