ELECTRON-BEAM-INDUCED PELLET FUSION*

Gerold Yonas UDC 533.9.621.039.6

I. Introduction

Relativistic electron beams have found wide use in fusion research in recent years, such as confinement of heating of magnetically confined plasmas, excitation of high-pressure gas lasers, and as high-intensity sources of energy for compression and heating of thermonuclear fuel. Sandia Laboratories has been engaged in several of these activities for the last few years, and this paper will discuss our recent experiments and theory leading to the implosion of pellets using electron beams.

The reasons for considering electron beams for pellet implosion include questions of practicality and cost. It is well known that electron-beam technology is relatively inexpensive and simple by comparison with that for lasers producing similar energies. Of course, at the present time electron-beam pulses are typically much longer than for lasers, but progress is being made in this area. If developments in pulse power and particularly in diode behavior continue, then we can look to electron beams to potentially provide a method for studying the physics of implosion and initiation of D-T burn. This would in itself justify support for such work even if electron beams did not ultimately proceed on to be used eventually in power-source application. On the other hand, if methods can be found to separate material surfaces from the point of energy release, and radiation-resistant materials are used in fusion reactor design, then the very high efficiency of electron-beam accelerators will considerably reduce the difficulty of producing power on an economically worthwhile basis. In addition, if one considers the use of a fission blanket instead of lithium to multiply the energy gain or to produce plutonium, then reactor concepts look plausible with only breakeven conditions [1]. Although pellets designed expressly for electron deposition are only now attracting attention, we have already seen recent calculations on the goal of creating interesting imploding targets and significant thermonuclear energy releases by focusing approximately a 1 MJ beam in 10 nsec onto a target of few millimeters diameter [2]. Although this goal is difficult, I believe it should be possible if we can extrapolate the impressive developments already achieved in electron beam physics and technology.

II. Beam Focusing

The goal of achieving fusion using electron beams would not have been considered very likely until experimental results in the last few years showed that in fact beams could be focused to the millimeter range. The first of such experiments involved the use by Bennett of a dielectric cathode in a high-impedance accelerator [3]. His early results caught the imagination of many groups, and we at Sandia began to study this effect in more detail. We found [4] in our experiments that beams would pinch down to a millimeter radius, confirming the results of Bennett and others [5]. We then sought to identify the focusing process. Mix and Kelly [6] used holography in such diodes (Fig. 1) and found that at the time of beam pinching, plasma which had accelerated from the cathode at velocities up to 10 cm/μsec and plasma moving from the anode at velocities of about 2 cm/μsec had closed, thus filling the gap with a charge-neutralizing background.

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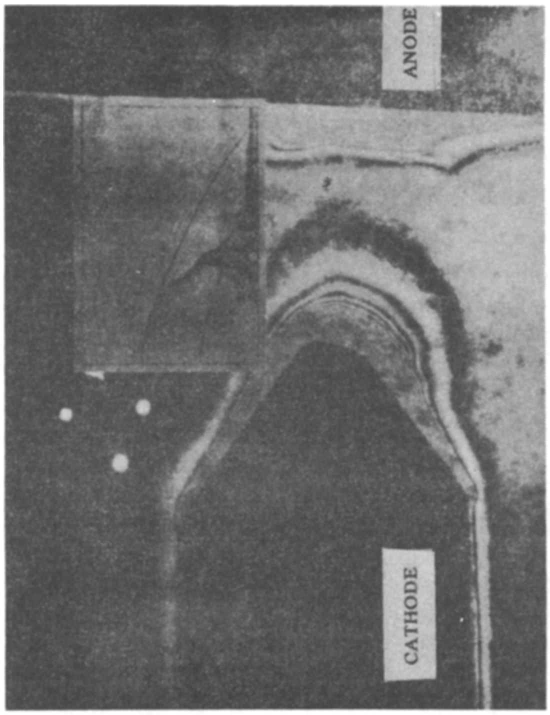


Fig. 1

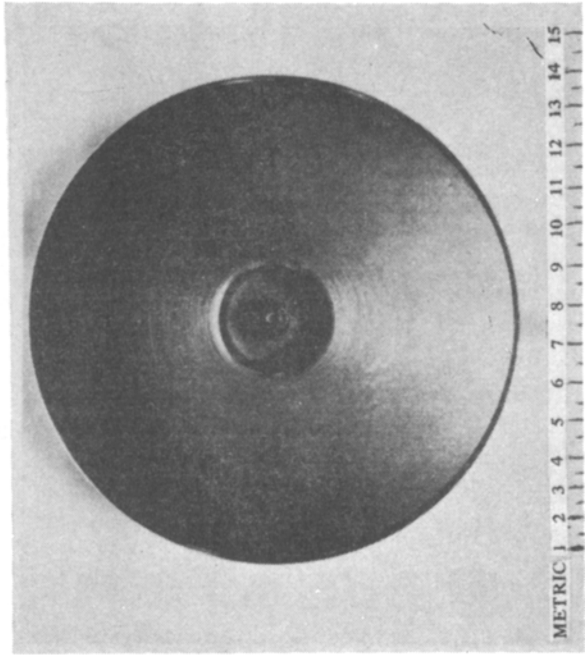


Fig. 2

Fig. 1. Holographic interferogram of plasma formation in diode with 0.6-cm-diameter glass cathode at time of plasma closure; insert shows results of particle calculation and envelope from fluid model.

Fig. 2. Cathode with field enhancement plasma source used on Hydra to produce 2-3 Ω impedance and focused beams.

Poukey and Toepfer [7] investigated this effect, namely space-charge neutralization in vacuum diodes, using both a 2-D particle in cell code and a finite-temperature relativistic fluid model. Since these diodes exhibited a rather high impedance, in the range of 10 Ω or more at the time of the formation of the pinch, and the holography showed that the diode was filled with plasma at that time, they speculated that the plasma would be sufficiently resistive (because of unspecified turbulent processes) that the electric field of the diode could uniformly penetrate the plasma. They carried out calculations which assumed space-charge neutralization and considered the effect of the combination of the magnetic field of a beam propagating in the plasma with the electric field on the diode. They found that the beam envelope was compressed by an order of magnitude or more over the distance between the cathode and the anode and that the kinetic energy acquired by the beam in acceleration across the gap became distributed primarily in the transverse direction, that is to say, a hot beam was produced. (Lawson [8] first studied the effect of a longitudinal electric field on a charge-neutralized beam, but for very restictive conditions, and he found similar results.)

With the fluid model, the explanation of the beam focusing can be simply understood. One finds that in order to maintain an equilibrium between the hot beam and the self-magnetic field, the beam radius must decrease significantly as shown in Fig. 1. As one can see, the particle calculations and the envelope calculation from the fluid model show good agreement for the final diameter of the beam. We conclude, therefore, that, through the natural formation from electrodes or through preinjection of plasma into diodes, tightly pinched beams can be formed (similar results have been observed with prepulse-created plasmas in diodes [9]).

From our experiments we have also found that if the diameter of the cathode is comparable to the anode-cathode gap, then the impedance of the diode will be in the range of 10 Ω even with a plasma-filled diode. With such a large impedance it will be impossible to achieve substantially greater than 10^{13} W at diode voltages in the megavolt range, and the very large inductance associated with the region between the small-diameter cathode and the vacuum insulator would prevent the achievement of a fast pulse risetime even if other sources of in-

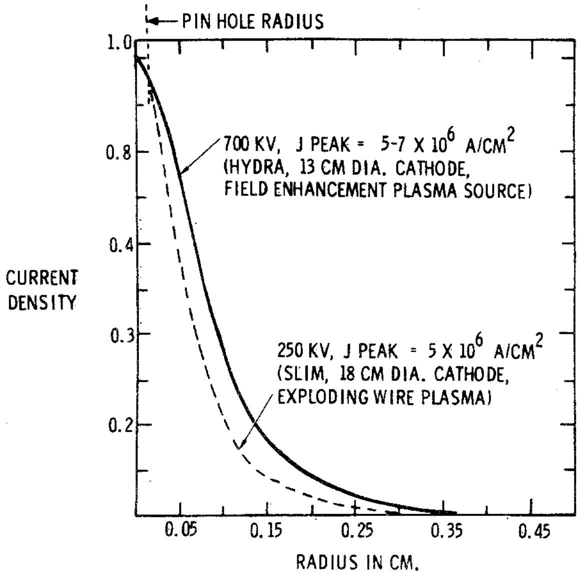


Fig. 3

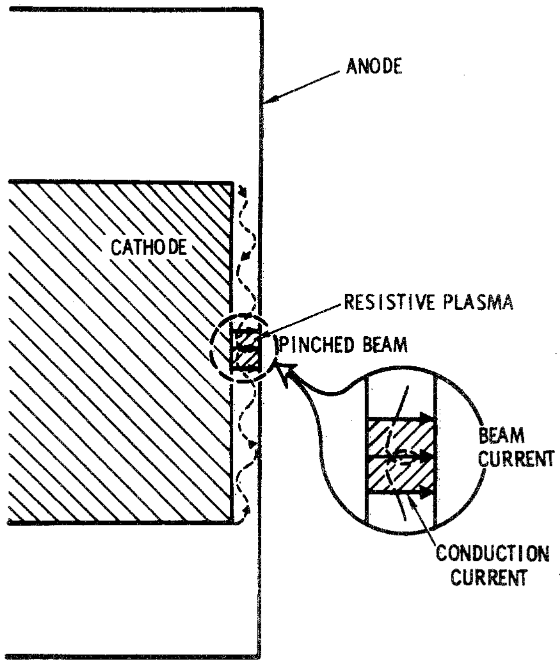


Fig. 4

Fig. 3. Current density distribution on anode.

Fig. 4. Schematic of low-inductance and impedance diode configuration.

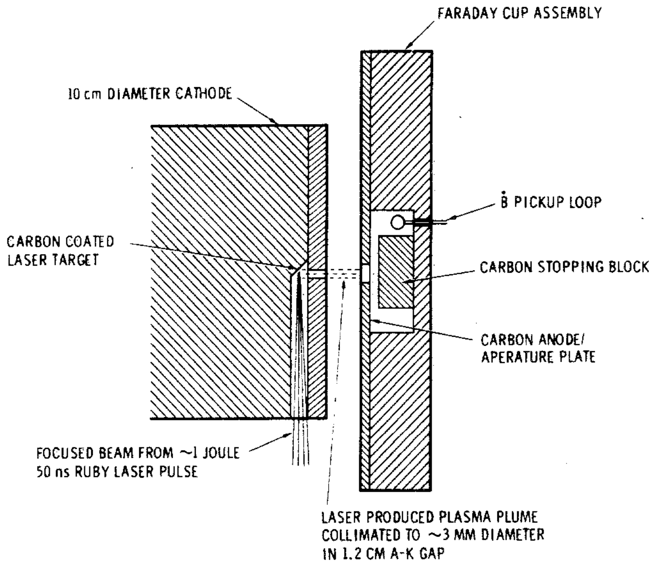


Fig. 5

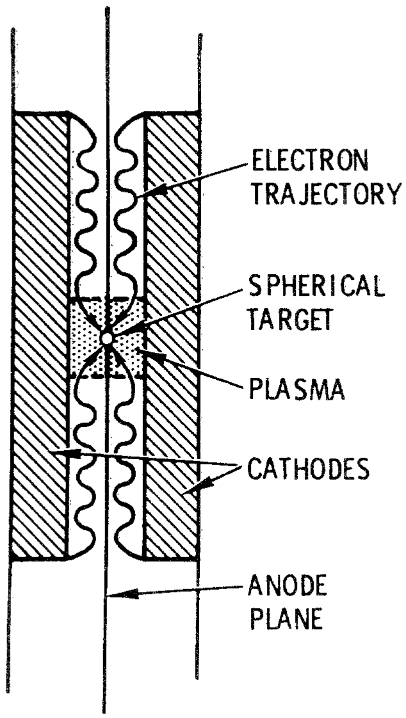


Fig. 6

Fig. 5. Laser plasma injection technique used on Hydra diode.

Fig. 6. Representation of an approach to achieve symmetric irradiation of a spherical pellet.

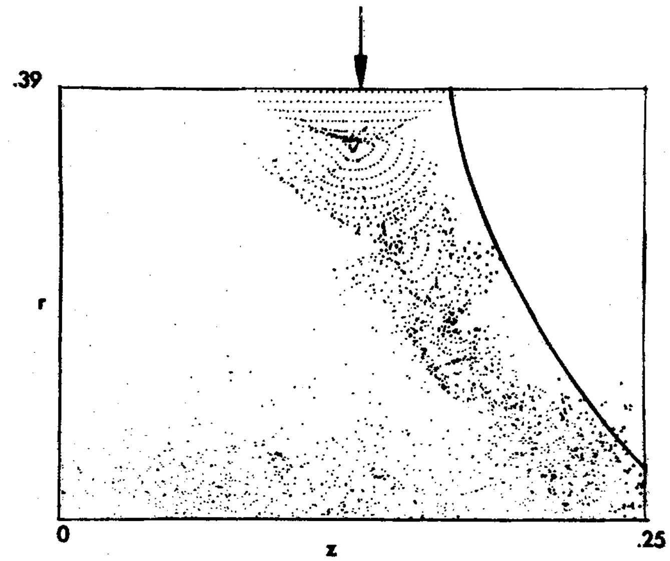


Fig. 7

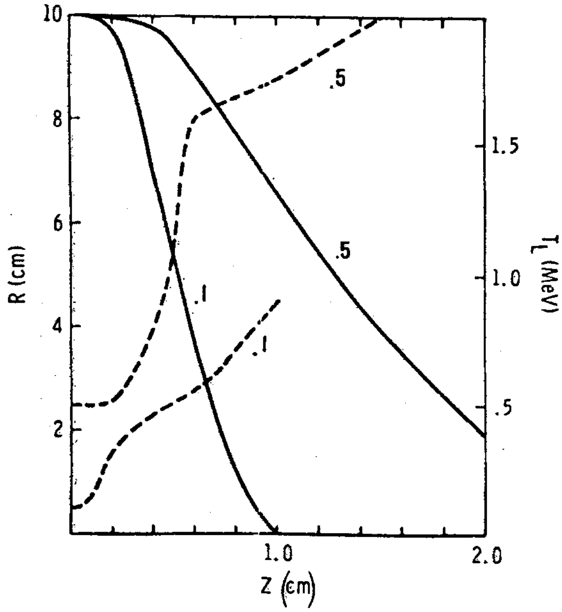


Fig. 8

Fig. 7. Particle density distribution from numerical solution and beam envelope from fluid model for a 2.5-MV, 300-kA beam.

Fig. 8. Beam envelope solutions for a 3-MeV, 3-MA beam with initial temperatures of 100 and 500 kV. Dashed line shows beam temperature as a function of longitudinal position.

ductance were eliminated. The question we must face is to find a diode configuration which will give not only a tightly focused beam, but also low inductance and impedance.

In Fig. 2 we see a cathode which is typically used on Sandia's Hydra accelerator [10] to approach these desired goals. In this case the diode impedance is 2-3 Ω, and this cathode allows us to reliably achieve a tightly pinched beam. The cathode is 13 cm in diameter, consists of Aquadag-coated brass, and has a hollow region in its center. A sharp-edged hollow emitter protrudes slightly from the face of the cathode ($\sim$ 1/4 mm), and in other cases we have used single needle points projecting from the face of the cathode. The anode—cathode gaps typically employed are approximately 1 cm. As we saw above, plasma can accelerate from a sharp-edged protrusion, and anode plasma can also enter the gap opposite the protusion early in the pulse. We should note that a prepulse isolation switch is employed in Hydra to prevent premature creation of diode plasma. In this passive manner, plasma is injected into the diode in the region of the central pinch during the pulse. Such a diode has been used to produce current densities in the range of 5-10 MA/cm^2 with a diode impedance of 2 Ω. In Fig. 3 we see a comparison of the beam current density profile at the anode as determined from time-integrated x-ray pinhole photography for the field-enhancement plasma source (beam energy is 10 kJ) as compared to results for a 1 kJ beam with an exploding wire plasma source [11].

A representation of the beam-focusing concept is shown schematically in Fig. 4. A large-aspect-ratio diode is employed to achieve both low impedance and low inductance, and a resistive plasma near the axis enhances the pinch without substantially reducing the diode impedance. As we have known for some time, if the current exceeds a critical value for which the Larmor radius of electrons at the edge of the beam is a fraction of the anode—cathode gap, then the beam will drift radially toward a central focus. By employing a region of charge-neutralizing plasma near the central focus, we are able to further reduce the diameter of the pinch by about another order of magnitude over that without plasma near the diode axis. We have thus been able to achieve a beam-diameter reduction from approximately 1 cm without plasma down to a value of a few millimeters with plasma.

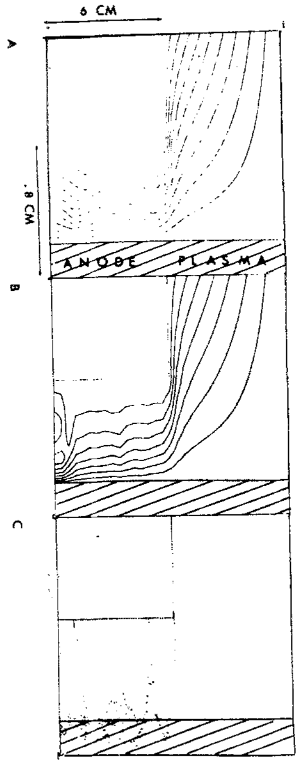


Fig. 9

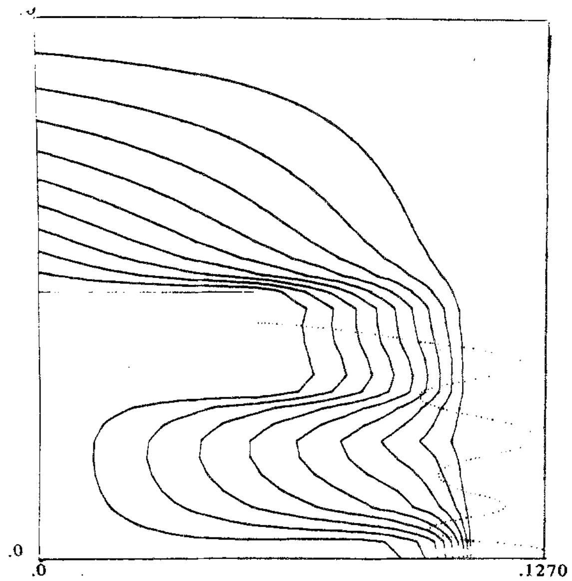


Fig. 10

Fig. 9. a,b) Initial and final equipotential distributions for 700-kV, 250-kA diode; c) Electron density distribution after quasi-steady solution is reached.

Fig. 10. Electron trajectory for a 700-kV, 250-kA hollow-cathode diode showing radial motion toward the region of central pinch.

In Fig. 5 we see one of the best controlled techniques for creating this plasma. In this experiment, Miller and Chang used an ∿ 1-J ruby laser to produce plasma blowoff from a region with the cathode. The plasma plume, which was collimated to approximately 3 mm diameter, entered the gap just prior to the electron-beam pulse. In this way they were able to achieve a reproducible beam focused to a diameter of a few millimeters.

The approach (Fig. 6) we have proposed for the use of such diodes in pellet-fusion studies is to employ two cathodes which face one another, with a region of plasma near the spherical target. The target is itself embedded or attached to a common anode foil. The electrons drift radially toward the pellet and then further pinch within the region of plasma. If the focused beams have a large fraction of their energy in transverse motion ("hot beam"), then the uniformity of irradiation should be quite good. This hot-electron-gas concept was merely an assumption in our early work and remains as a critical issue, although recent experiments have tended to support such an interpretation.

With these experimental results in mind, let us return to the question of the effect of the longitudinal electric field and its role in pinching of a space-charge-neutralized beam [7].

We consider a case representing an experiment we hope to do sometime in the future. In Fig. 7 we see both numerical results and the beam envelope derived from the fluid model (shown by the solid line) for the case of 300-kA beam injected into a region of plasma ∿ 0.40 cm in radius. The applied voltage is 2.5 MV (ν/γ ∿ 3) and we find a peak current density of roughly 100 MA/cm^2 at the anode. In this case the numerical calculation is in good agreement with the fluid model with the understanding that the solution for the fluid model is extremely dependent on the initial temperature assumed for the beam. This dependence on initial temperature is shown to be more pronounced in Fig. 8 where we consider a 3-MeV, 3-MA beam (ν/γ ∿ 30) with an initial radius of 10 cm and an electric field of 1.5 MV/cm applied across a gap of 2 cm. We consider the envelope solution for two different values of initial

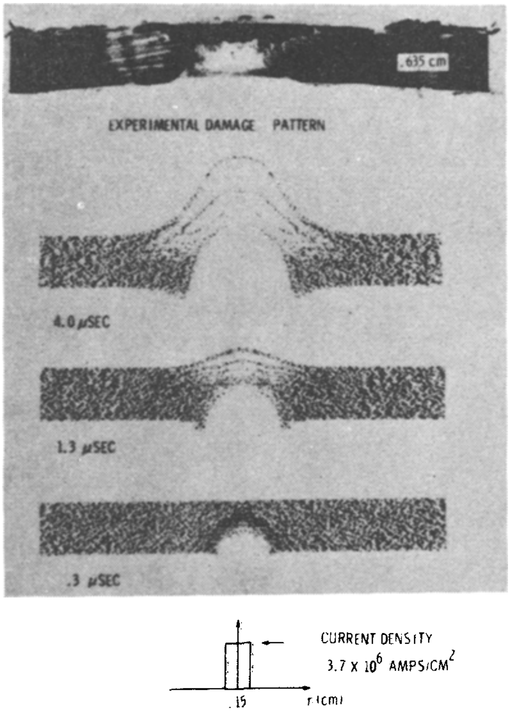


Fig. 11

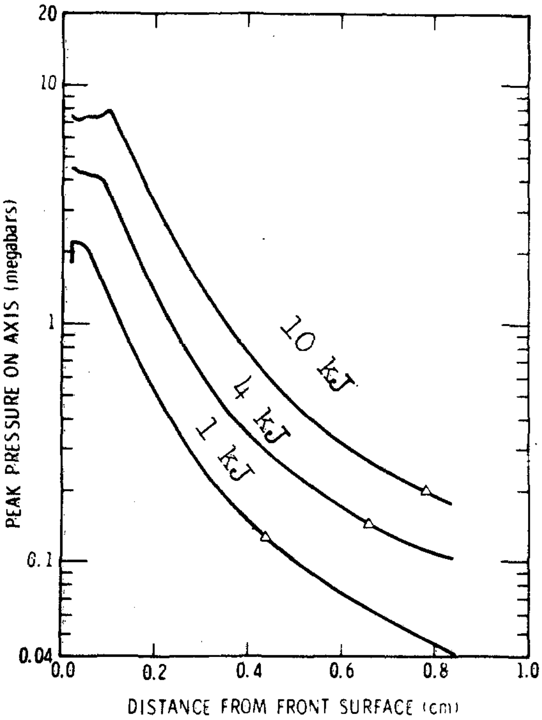


Fig. 12

Fig. 11. Calculation of crater formation in aluminum target and comparison with sectioned sample.

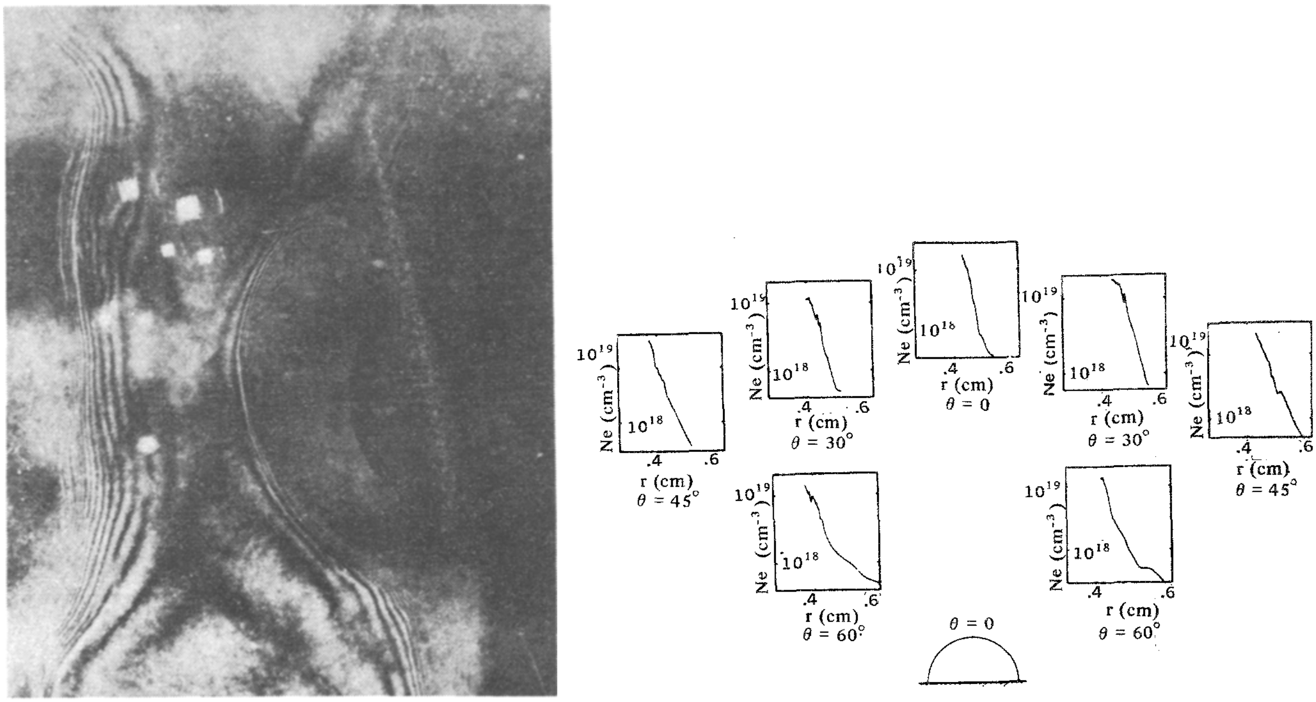
Fig. 12. Calculated envelopes of propagating stress waves in aluminum and crater depth, shown by triangles, for 1, 4, and 10 kJ deposited.

beam temperature; 500 and 100 kV. In the case of the 100-kV initial temperature, the beam pinches down to a negligible radius before it reaches the anode; it is observed to reach stagnation conditions; there is no longitudinal motion and the fluid model breaks down. On the other hand, if the initial temperature is 500 kV, the final beam radius is restricted to a few centimeters. Again we observe from the fluid model that the assumed initial temperature of the beam has a strong influence on its final diameter and may be one of the most important parameters to control.

Returning to calculations describing present experiments, we consider diodes employed on Hydra and consider beam focusing outside of the plasma region near the diode axis. The Hydra diode typically operates in the range of 700 KV with currents of roughly 300 kA. In these calculations we consider the drifting of electrons toward the central focus discussed above. In Fig. 9 we observe (a) the vacuum equipotentials, (b) the final equipotential distribution, and (c) a representation of the charge distribution after a quasi-steady state is reached. The anode plasma is assumed to exclude the electric field of the diode but to permit the self-magnetic field of the beam to penetrate uniformly. This assumption is reasonable for nominal parameters for the anode plasma.

We note, first, that the charge concentration near the axis produces an electric field near the anode roughly an order of magnitude greater than in the vacuum case prior to charge injection, and second, that the electrons are observed to be emitted primarily from the outer edge of the cathode, cross to the anode, and then drift radially downward in a complex motion that will be discussed later. One also notices the superficial resemblance to the "parapotential" [12-13] model.

When the electrons reach the region of the axis, the electric field dominates over the magnetic field, and the electrons are accelerated toward the anode. Near the axis, if one provides a region of charged-neutralizing resistive plasma, then the beam will pinch further from a dimension comparable to the anode—cathode gap down to a few millimeters or less. As mentioned earlier, the mechanism responsible for the anomalously high plasma resistivity near the axis is not understood but may be a result of a beam-driven instability.



a b

Fig. 13. a) Holographic interferogram of hemisphere irradiated on Hydra; b) radial density profiles after Abel inversion.

One of the most interesting features that has resulted from these calculations (and potentially a critical issue in reactor design considerations) is that very similar diode behavior will occur if the cathode is hollow (Fig. 10). With a hollow cathode the impedance is unchanged from a solid one and a pinch is formed, but the focus is not as concentrated as for the case when plasma is injected. Because of the charge concentration near the axis, the electric field is found to be very similar to that with a solid diode. The electrons are seen to drift across the diode, cross the gap, and are then focused near the axis. We also note a typical trajectory and point out the behavior of the electrons in their radial drift toward the axis. The self-magnetic field returns electrons to the vacuum region from the anode region, and the diode electric field then brings electrons back to the anode plasma. The radial drift continues until electrons reach a region near the axis. In these numerical calculations, we admit that a greatly oversimplified treatment of anode plasma has been used and the diode-plasma model is being studied to provide agreement with impedance scaling as well as time-dependent beam behavior.

III. Deposition Experiments

The main thrust of the recent experimental work has been on the Hydra accelerator [10] which is essentially two water-insulated, coaxial, pulse-forming lines fed from a common 3-MV Marx generator. The two 4-Ω pulse-forming sections and two-to-one impedance-reducing transformers can either be used independently or fired synchronously using triggered gas switching.

In order to evaluate the efficiency of focusing and coupling of beams on thick anodes, Widner has employed a two-dimensional hydrodynamic code with a multiphase equation of state to calculate the crater-formation process. In Fig. 11 we see the time evolution of the crater for a 10-kJ beam deposited in a time period of 50 nsec with a beam radius of 0.15 cm. The shock wave in propagating through the target compresses and heats the material to melt conditions. The molten material is ejected from the crater, producing the crater to a depth governed by the attenuation of the initial shock wave. The final crater is then compared with a sectioned sample as shown here and allows one to estimate the energy absorbed by the beam. In Fig. 12 we see the envelopes of the propagating stress wave as a function of distance into the material for three different assumed energy input values. The depth of

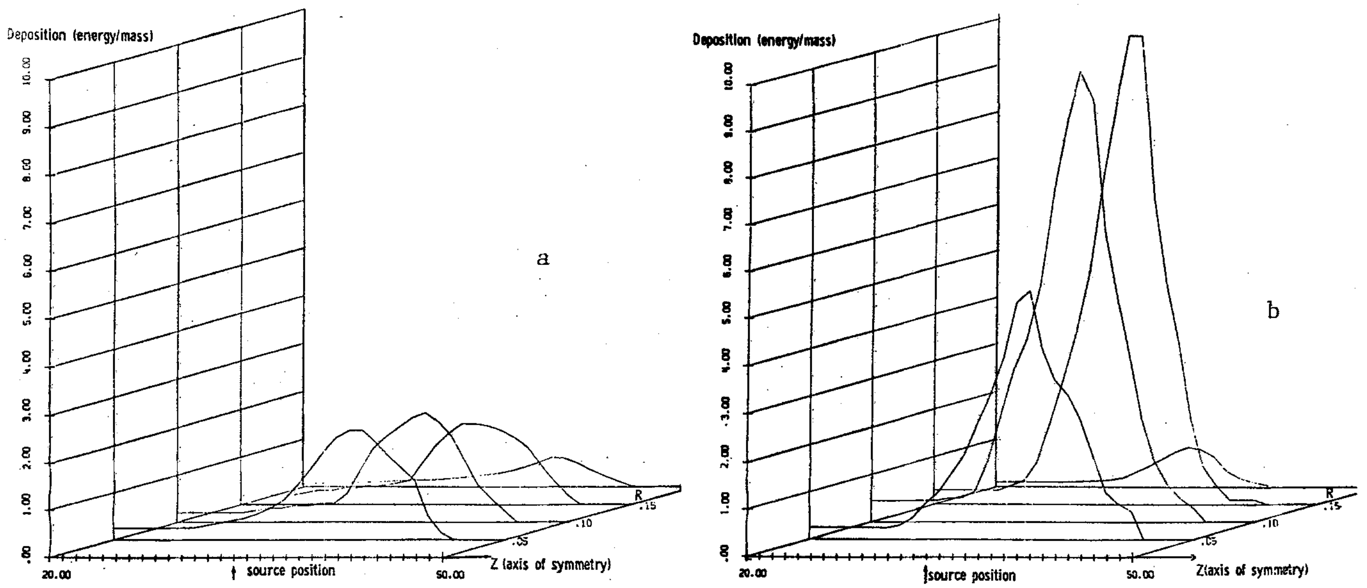


Fig. 14. Energy deposition distribution in exponential density blowoff from gold target: a) no magnetic field; b) with self-field of 350 kA, 0.15-cm-radius beam.

the crater, as shown by the triangles for the cases of 10, 4, and 1 kJ, is a strong function of the energy input, and the size of the crater can be correlated with the energy absorbed in the target as long as the beam focal spot is smaller than the final crater size.

This gross measurement of the crater formation has served as a prelude to more quantitative studies of deposition as evidenced by the shock-generation process. In the first of such more detailed experiments, Perry has used an interferometric laser velocimeter to record motion of the rear surface of a target. The shock arrival time has corroborated the existence of megabar pressures near the front surface and has shown no evidence for anomalously short deposition characteristics. Studies of this kind are continuing and are expected to play a vital role in our understanding of the deposition process.

Although we are just beginning to study flat targets and deposition, Toepfer and Mix have recently begun to investigate the response of hemispherical gold shells. They have used the cathode shown in Fig. 2 with a hemispherical shell attached to the anode. Holographic interferograms (Fig. 13) were taken of the region of the target showing the plasma from the cathode protrusion as well as the blowoff plasma from the hemispherical shell. Although target alignment was not perfect in this shot, the relative symmetry of the blowoff is seen to be surprisingly uniform, and there is no evidence of beam breakup into multiple filaments in the blowoff plasma.

In order to employ this type of data quantitatively, the interferogram can be used, after an Abel inversion, to give the radial density distribution for various angles (Fig. 13b). At 60° we see evidence of anode plasma surrounding the pellet, but within the region outside the anode plasma we clearly see the radial blowoff which is shown to be relatively uniform. There is no evidence of interaction with the self-magnetic field or other anomalous effects of the beam, and the target expands freely into the vacuum. Because of the lack of perturbation of the blowoff, one might be led to conclude that the magnetic field had penetrated the plasma and, as we shall see, the beam self-field can effect energy deposition. We have called this effect "magnetic stopping" [14].

Halbleib and VanDevender have begun to study the effect of the self-magnetic field of the beam on energy deposition in the blowoff region using a Monte Carlo electron transport code. They have modeled the target blowoff by referring to interferometric measurements of the gold blowoff in hemishell targets and have considered the case where the material has expanded with exponential density falloff from the front surface. The beam is incident onto

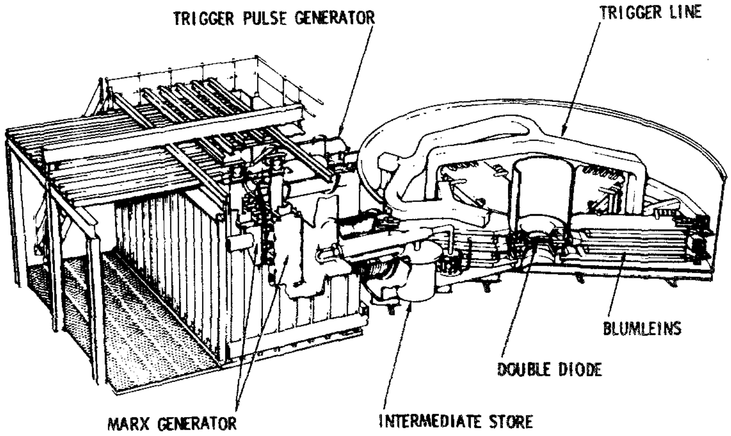


Fig. 15. Design of a 2×10^{12} W, 3.0-MV accelerator.

a flat target from the position shown in Fig. 14 in the blowoff. The effect of possible current neutralization is not considered self-consistently, but they have attempted to evaluate the relative importance of expected fields by comparing cases of full and zero current neutralization. Assuming complete current neutralization (no magnetic field) and no applied electric field in the blowoff, we find that the deposition is uniform with radius (Fig. 14a). The dose is that expected for classical deposition, and 73% of the incident beam is absorbed. On the other hand, if one allows the self-magnetic field of the beam to enter the blowoff region, then near the axis the dose is increased by a factor of about 2 over the no-field case, and near the edge of the beam the dose is increased by almost a factor of 5 (Fig. 14b). Of course, the energy is deposited in less dense material than in the zero-field case, although the energy absorption is increased to 95%. Although there are many simplifying assumptions in such calculations, they serve to point out four things: the self-magnetic field of the beam (1) can be important in the blowoff region, (2) can enhance the deposition, (3) can effectively shorten the range, but (4) can lead to asymmetries. These results also point out the importance of time resolved x-ray diagnostics, both during and after the beam pulse, for determining the behavior of the dense blowoff region and symmetry of imploding targets which will not be visible with optical diagnostics.

IV. REB Accelerator Development

In order to carry out spherical implosion experiments, the two lines of Hydra will be synchronized using triggered gas switches, the diodes will be extended using vacuum coaxial cylinders which are magnetically insulated, and a pellet will be inserted in a solid anode. Flash radiography will then be employed to study implosion symmetry, and neutron diagnostics will be used for suitable targets. We expect that an experiment of this kind will be carried out with a total beam energy in the range of $\leq$ 20 kJ hopefully within this year.

In the future it will be necessary to construct an accelerator primarily for applications to pellet fusion, and such an accelerator is proposed to employ two disk-shaped pulse-forming lines feeding a common anode. A 2×10^{12} W, 3.0-MV prototype of such a device is under construction now and is shown in Fig. 15. It consists of six pairs of Blumleins fed from a single Marx generator. The energy is fed from the Marx generator into intermediate water-insulated energy-storage capacitors in order to minimize the electrode spacings in the Blumleins and thus the diameter of the accelerator. The Blumleins employ triggered oil switches [15] which consist of two smooth, rail-type electrodes and a sharp-edge trigger electrode which is biased at an equipotential of roughly one-third the applied voltage prior to the application of the trigger pulse. A fast trigger voltage of opposite polarity but comparable in magnitude to the gap voltage is applied, initiating multiple streamers. When the number of spark channels exceeds roughly eight to ten over a distance of 1 m, the remaining portion of the risetime is independent of the number of channels (the resistive phase) and the relative jitter is less than 2 nsec.

V. Conclusion

As we have seen, there are many problems which must be dealt with if we are to achieve successful pulsed fusion using electron beams. In order to accomplish this goal, there are three crital areas of physics which will require substantial clarification: (1) beam focusing in low-inductance diodes, (2) symmetric input to the target, and (3) energy deposition in the outer region of the pellet. The accelerators we now have and are planning to build in the near future should provide the needed basis of fundamental understanding. If beams can be focused efficiently down to the millimeter sizes at power levels of $\sim 10^{14}$ W, then extremely interesting implosion studies can be carried out. If these prove successful within the next several years, then we may be able to go onward toward producing prototype fusion reactors, and much later, if many technical problems are solved, practical fusion power may follow.

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LITERATURE CITED

1. S. G. Varnado, V. L. Dugan, R. D. Klett, R. H. Richards, and S. G. VanDevender, "Preliminary systems considerations for an electron-beam-induced fusion power plant," SAND-74-0160, September 1974.
2. L. I. Rudakov and A. A. Samarsky, Proc. 6th European Conf. on Controlled Fusion and Plasma Phys., Moscow, July 1974, pp. 487
3. W. H. Bennet, Bull. Am. Phys. Soc., 19, 669 (1972).
4. L. P. Bradley and G. W. Kuswa, Phys. Rev. Lett. 29, 1441 (1972).
5. W. C. Condit et al., Phys. Rev. Lett. 30, 123 (1973).
6. L. P. Mix, J. G. Kelly, G. W. Kuswa, D. W. Swain, and J. N. Olsen, J. Vac. Sci. Tech., 10, No. 6, 951 (1973).
7. J. W. Poukey and A. J. Toepfer, "Theory of super-pinched relativistic electron beams," to be published in Phys. Fluids.
8. J. D. Lawson, J. Electron., 3, 587 (1957).
9. A. V. Gordeev, V. D. Korolev, Yu. L. Sidorov, and V. P. Smirnov, Conf. on Electrostatic and Electromagnetic Confinement of Plasmas and Phenomenology of the Relativistic Electron Beams, New York, March 1974.
10. T. H. Martin, IEEE Trans. Nucl. Sci., Vol. NS-20 (1973), p. 289.
11. G. Yonas, K. R. Prestwich, J. W. Poukey, and J. R. Freeman, Phys. Rev. Lett. 30, 164 (1973).
12. D. dePackh, Naval Res. Lab. Rad. Proj. Int. Rep. 7 (1968).
13. J. Creedon, Phys. Int. Internal Report 19-17 (1970).
14. G. Yonas, J. W. Poukey, K. R. Prestwich, J. R. Freeman, A. J. Toepfer, and M. J. Clauser, "Electron beam focusing and application to pulsed fusion," to be published in Nuc. Fusion.
15. K. R. Prestwich, "A 2 MV, Multichannel, Oil-Dielectric, Triggered Spark Gap," International Conf. on Energy Storage, Compression, and Switching, Torino, Italy, November 5-7, 1974.
16. T. H. Martin and K. R. Prestwich, "EBFA, A high-power electron beam accelerator,"