at other angles, including 90° scattering from thick samples, and the ratio of slopes has consistently turned out to be close to 1.45. By use of the theory of de Gennes[8] with the approximations mentioned previously,[6,7,12] $I_{VV}^{-1} \propto a(T-T^*) + L_1 q^2$ and $I_{VH}^{-1} \propto \frac{4}{3} I_{VV}^{-1}$. Although the observed linear behavior of the reciprocal intensities is consistent with the theory, the theory predicts that $(\partial I_{VH}^{-1}/\partial T)/(\partial I_{VV}^{-1}/\partial T) = \frac{4}{3}$ in disagreement with our data.

We have investigated the effect of a background contribution to the polarized component of the scattered light, either from impurities or from stray scattered light.[5] Such a contribution would have an intensity and spectral line shape that would be essentially temperature independent. Although this would cause the $I_{VV}^{-1}$ data to bend away from the $\frac{3}{4} I_{VH}^{-1}$ line in Fig. 3, attempts to fit the data with such an assumption do not produce a better fit than the straight line in Fig. 3 labeled $I_{VV}^{-1}$. Furthermore, the effect would produce a second component in our line shapes which we do not see.

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# Two-Dimensional Calculation of Electron-Beam–Target Interaction

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The interaction of a pinched relativistic electron beam with a solid target is calculated by use of the Monte Carlo method for energy deposition and two-dimensional particle-in-cell (PIC) hydrodynamics to take into account the full effect of target expansion. Bremsstrahlung emission is also evaluated through the use of the Monte Carlo method. Self-magnetic-field effects are neglected. It is found that target expansion can considerably reduce the efficiency of energy deposition in the focal region.

The use of relativistic electron beams for an inertially confined controlled thermonuclear reaction involves obtaining high energy densities in solid targets by pinched-beam energy deposition.[1-4] Considerable effort is devoted to obtaining highly pinched electron beams.[5-10] The process of energy deposition in the high-current, high-energy-density regime differs from the classical cold-target process in a number of ways. One of these is the effect of target expansion due to the high pressures which develop during the energy-deposition process. In cold high-density targets the penetration depth of a typical beam (say, 500 keV) is much smaller than a typical obtainable pinch radius. Therefore, in a cold dense target, an electron which is scattered sideways during the process of slowing down still has a good chance to deposit its energy in the focal region. Later in the pulse, matter initially in the focal region expands and the expanding column is much more "transparent" to electrons in the lateral direction. Therefore, an electron entering the expanded target material has a better chance to escape without depositing its energy if it is scattered sideways. This effect is expected to be important whenever

$$\bar{\rho} R < \rho_0 d \quad \text{or} \quad l + d > R, \qquad (1)$$

where $\rho_0$ is the initial density, $\bar{\rho}$ is the average expanded material density, $R$ is a typical lateral dimension of the expanding material of the order of the pinch radius, $d$ is the penetration depth into the cold target, and $l$ is a typical backward expansion distance. One-dimensional calculations of beam-target interaction in a typical experimental situation (5 kJ of 350-keV electrons into 0.1 $cm^2$ of tungsten target in 100 nsec) indicated that indeed criterion (1) is expected to be fulfilled before the end of the pulse, and therefore a considerable reduction of the energy-deposition efficiency may occur.

The purpose of this work is to evaluate the importance of two-dimensionality on the energy-deposition efficiency by detailed energy-deposition and hydrodynamical-expansion calculations, and also to examine the possibility of using the bremsstrahlung emission as a diagnostic tool in measuring the effect.

The calculations consist of essentially three phases. Phase I is the calculation of energy deposition by the beam in the given density distribution. Phase II is the calculation of hydrodynamic motion which follows. At the end of this phase one goes back to phase I to calculate the energy deposition in the new density distribution, etc. In Phase III the density distributions obtained in phases I and II are used in a separate calculation to determine the bremsstrahlung emission from the target.

*Energy deposition.*—The calculation is performed by the Monte Carlo method in a way similar to that described by Berger.[11] We use the continuous-slowing-down approximation and Molière's[12,13] multiple-scattering theory. The situation met under conditions of interest here may make certain assumptions and approximations less valid than they are in the cold-target, low-current-density case. We use only the classical slowing-down processes while it may well be that partial current neutralization in the target may shorten the effective range of the electrons through the effect of the self-magnetic-field of the beam. We neglect possible temperature corrections to the effective ionization energy $I$ in Bethe's[14] slowing-down theory and take it to be 748 eV for tungsten.[15] Plasma effects on the characteristic screening angle used in Molière's multiple-scattering theory are also neglected here. It is assumed in the calculation that the target is the anode of a diode and that an accelerating field exists in the anode-cathode gap, which drives backscattered electrons into the target.

We have no rigorous model of the pinch. We therefore calculate two extreme cases: a "laminar" parallel beam and a "turbulent" converging beam. In the first case the electrons are assumed to hit the target vertically to its initial surface and the beam diameter is equal to the focal-area diameter. In the second case we assume a converging beam hitting the focal area with a conical contour line making an angle of 20° with the initial surface of the anode. At each point of entry the electron direction is chosen at random from a distribution bounded by a cone making the same angle with the initial surface.

At each energy-deposition step 5000 case histories are followed. This number provides statistical fluctuations which are not larger than those generated by the density fluctuations of the hydrodynamic calculation at the mesh size and number of simulation particles used.

*Hydrodynamics.*—The two-dimensional, cylindrically symmetric, hydrodynamic expansion of the target is calculated by the particle-in-cell (PIC) method, following Harlow[16] and Amsden.[17] The equation of state used essentially follows that of Al'tshuler *et al.*[18] In order to avoid excessive computer time consumption, the Monte Carlo energy-deposition calculation was not performed at each time step, but at each ten time steps. At the time steps which follow a calculated deposition profile the *power* deposition is assumed to be a constant Lagrangian property of the moving simulation particles. In the particular problems studied in this work the mesh size was $dr = 0.003$ cm in the radial direction and $dz = 0.0015$ cm in the axial direction. The whole flow field was covered by 50 (radial) × 132 (axial) cells. The cold target was 50 (radial) × 20 (axial) cells of tungsten, with 16 particles per cell.

*Bremsstrahlung emission.*—Radiative energy losses at electron energies of interest here are not very important. Energy deposition through self-absorption of the bremsstrahlung was therefore not considered and the detailed calculation of bremsstrahlung emission can therefore be decoupled from the hydrodynamics. The emission is calculated separately, with use of density profiles obtained beforehand from the hydrodynamical calculations. The cross sections used for the bremsstrahlung Monte Carlo calculations are based on estimated experimental corrections to the Born approximation.[19-21]

Calculations were performed for the following case: a square pulse of (5 kJ)/(100 nsec) of 350-

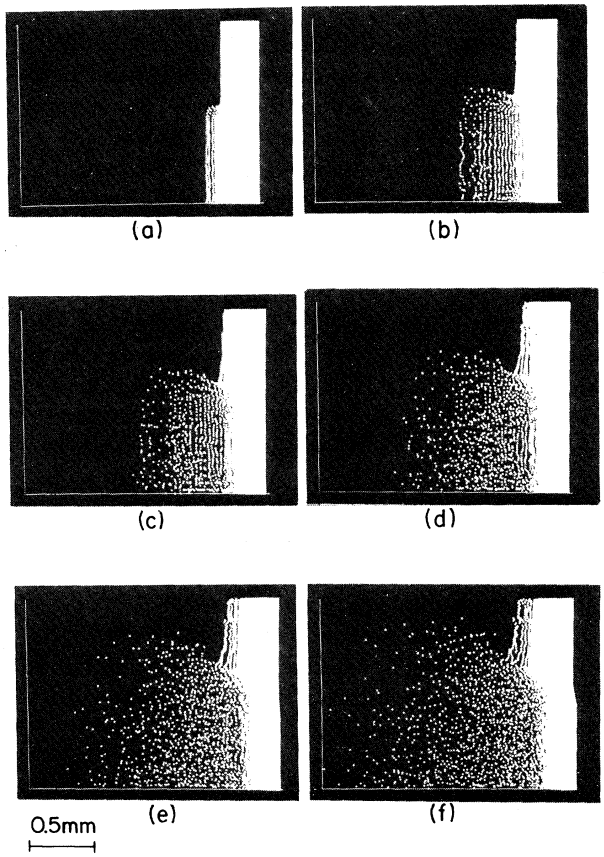


FIG. 1. Successive snapshots of the hydrodynamic expansion at times (a) 10, (b) 20, (c) 25, (d) 30, (e) 35, (f) 40 nsec from the start of the pulse; parallel-beam model.

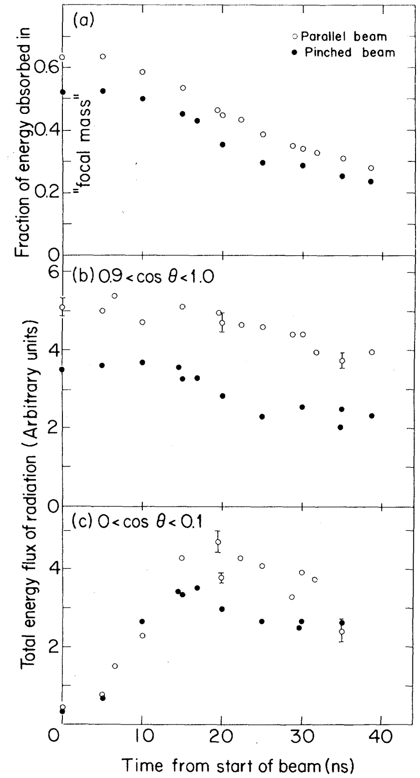


FIG. 2. (a) Energy-deposition efficiency as a function of time in parallel- and pinched-beam models. (b) Bremsstrahlung emission in the forward direction in the 25.8° angle in both beam models. Error bars indicate fluctuations in Monte Carlo energy-deposition results. (c) Bremsstrahlung emission in the 90° direction into 16° angle in both beam models. Error bars the same as in (b).

keV electrons hitting a focal area of 0.75 mm radius on the initial target surface. The target material is tungsten. The "parallel"- and "pinched"-beam cases were studied.

"Snapshots" of the hydrodynamic expansion at various times are shown in Fig. 1. The process was only followed until 40 nsec after the start of the pulse, because at that time the two-dimensional effects were already pronounced. Energy-deposition rate as a function of time in the focal mass (mass inside the initial focal area) is shown in Fig. 2(a) for the parallel- and pinched-beam models. The rest of the energy is deposited outside the focal area, as may be seen in Fig. 1, or else outside our mesh. Energy deposition outside the focal area takes place by electrons backscattered or sidescattered into the gap and driven towards the anode by the accelerating field. As can be seen, the deposition efficiency drops by a factor of approximately 2 by the time of 35 nsec from the start of the pulse. The statistical fluctuations in the Monte Carlo energy-deposition results are of the order of 1.5% and those due to density fluctuations in the PIC calculation are of the order of 2%.

The chances to observe this drop in depostion efficiency through the bremsstrahlung yield can be inferred from Figs. 2(b) and 2(c) where the focal-area yields in the forward and 90° directions are shown as functions of time in both beam models. It is interesting to note that the relative drop in bremsstrahlung yield in the forward direction is less than the drop in deposition efficiency. This effect is connected with the fact that the bremsstrahlung emission is essentially peaked in the electron direction. The radiation emitted by an electron scattered sideways is lost both in the dense and in the expanded target,

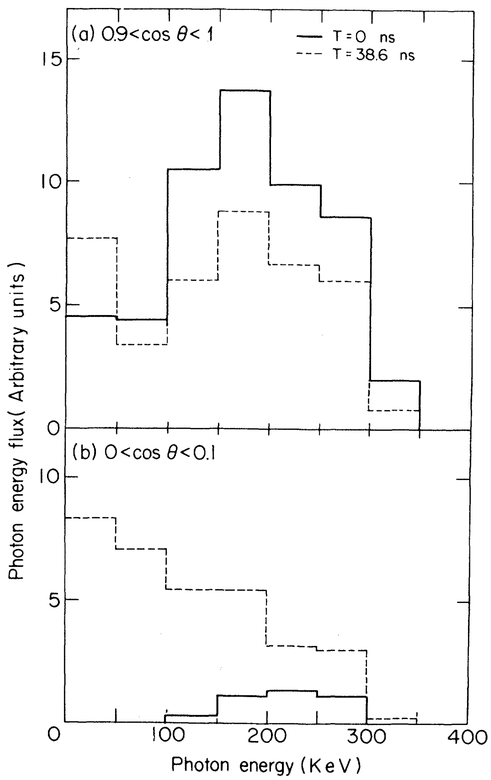


FIG. 3. (a) Bremsstrahlung energy-flux spectrum in the forward direction. (b) Bremsstrahlung energy-flux spectrum in the 90° direction. Parallel-beam model.

while its energy is lost only in the expanded target.

Bremsstrahlung detection in the 90° direction is strongly influenced by the self-absorption of the photons in the target. In this case it is only possible to observe the radiation after some backward expansion has taken place. The error bars in Fig. 2(c) are due to the fluctuations in the energy-deposition Monte Carlo program. The large spread in the results at 20 nsec is due to the density fluctuations in the PIC calculation. These fluctuations strongly influence the 90° radiation since this radiation results mostly from the expanded part of the target. Bremsstrahlung spectra in the forward and 90° directions at the start and 35 nsec after the start of the pulse are shown in Fig. 3.

In conclusion, we have demonstrated the importance of two-dimensional expansion effects in obtaining efficient energy deposition by electron beams in solid targets. In particular, 100 nsec may be too long a pulse for efficient deposition of 5 kJ of 350-keV electrons into a 0.75-mm focal spot on a high-density target.

Self-magnetic-field effects are neglected in this work. Estimates based on non-self-consistent calculations assuming zero current neutralization in the target blow-off mass[2] indicate that these effects can increase the energy-deposition efficiency. The beam self-magnetic-field in the gap may hinder escape of electrons from the focal area and thus significantly alter our conclusions. Further work on this subject is in progress.

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# Irradiation of a Spherical Target by a Single Relativistic Electron Beam*

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An experimental study of irradiation of spherical targets by single relativistic electron beams has been conducted to determine deposition symmetry. A 700-keV, 300-kA, 100-nsec beam was used with diagnostics consisting of x-ray pinhole photography, flash radiography, and evaluation of anode-backing-plate damage. The degree of symmetry was typically much better than 2:1 over the target surface, indicating that single-beam irradiation could be an acceptable approach to pellet fusion.

Ablation-driven implosion of DT-filled, high-density spherical shells using highly focused, intense, relativistic, electron beams (REB's) has been proposed as an approach to inertial-confinement fusion.[1] REB's are attractive because by using existing and developing REB technology, large energies with high system efficiency can be achieved. In this approach the high-density shell is chosen to be sufficiently thick to absorb the beam energy efficiently in its outer region, with the inner portion of the shell thus becoming an unheated hypervelocity pusher,[2] which can compress, heat, and finally, after ignition, confine the DT. In the explosive rather than ablative approach the high-density shell is heated uniformly by a REB with a depth of penetration many times the shell thickness.[3] In both cases, it is critically important that a highly uniform, spherically symmetric implosion be achieved to obtain compression ratios of ~ 1000 as needed for achieving high fusion yields. We therefore require that electrons be incident on the target with a uniform energy flux over the entire surface. In this paper we report results of experiments to determine the symmetry of loading of a spherical target with a single tightly focused beam.

It has been proposed that self-focused beams in large-aspect-ratio diodes will have a sufficiently large spread in angles such that fluid properties can be ascribed to the beam. As such it was suggested that spherically symmetric deposition would be obtained on a target irradiated with two opposing beams.[1,4,5] Here we extend the concept to single-beam irradiation of a spherical target, which, if successful, can reduce the complexity of fusion experiments. In particular, single-beam irradiation would be possible with many of the high-power REB accelerators now in existence.

In the experiments described here a 0.4-cm-diam spherical target was irradiated with a single 700-kV, 300-kA, 100-nsec beam from the Hydra accelerator.[6] The target was either a hollow 0.03-cm-wall-thickness gold shell, or a solid brass sphere, attached either directly to a 0.625-cm-thick copper anode or suspended on a 0.1-cm-long aluminum stem from the anode (Fig. 1). Without a target present, the diode used in these experiments has reproducibly formed pinched beams. The question of achieving spherical irradiation with a single pinched beam was addressed here through experiments and comparison with two-dimensional hydrodynamic-code calculations. The diagnostics consisted of the following as depicted in Fig. 1.

(1) Time-integrated x-ray pinhole photography (a) along and (b) normal to the diode axis was used to determine the uniformity of bremsstrahlung emission from the target.

(2) X-ray shadowgraphy using a second x-ray source (c) and a time-gated electronic x-ray camera[7] (d) was used to determine the dynamic response of the target after the shot.

(3) Comparisons of the appearance of the backing plate (e) with hydrodynamic-code results were made in order to infer the degree of jetting caused by asymmetric shell implosion.

In Fig. 2 we see the x-ray pinhole images of a

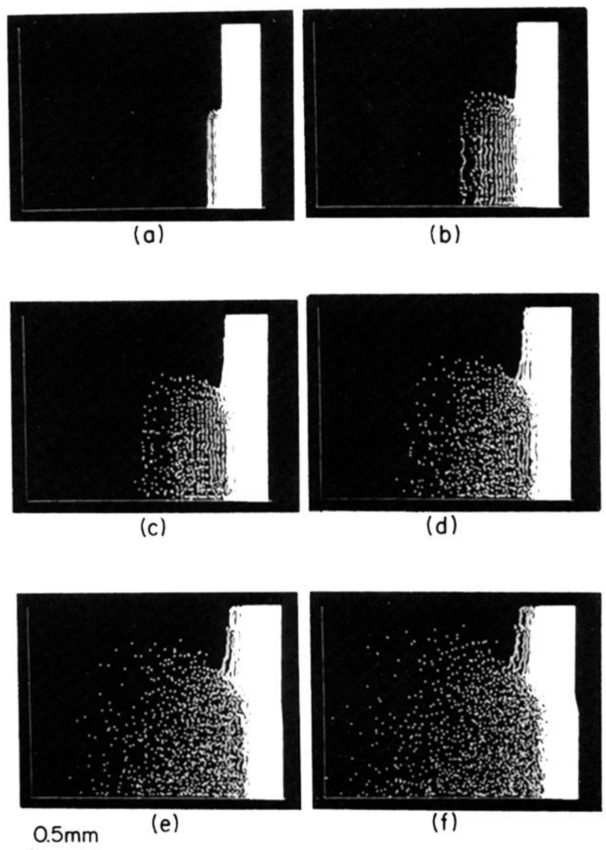


FIG. 1. Successive snapshots of the hydrodynamic expansion at times (a) 10, (b) 20, (c) 25, (d) 30, (e) 35, (f) 40 nsec from the start of the pulse; parallel-beam model.