[13]A. Fahlman, R. Nordberg, C. Nordling, and K. Siegbahn, Z. Phys. 192, 476 (1966).
[14]E. J. McGuire, Phys. Rev. 185, 1 (1969).
[15]O. Sinanoglu, Nucl. Instrum. Methods 110, 193 (1973).
[16]J. P. Buchet and M. C. Buchet-Poulizac, Phys. Lett. 46A, 273 (1973).
[17]E. J. McGuire, Phys. Rev. 175, 20 (1968).
[18]E. J. McGuire, to be published.
[19]P. H. Citrin, Phys. Rev. B 8, 5545 (1973). This work indicates that the Auger spectrum in Ref. 12 assigned to Na_2O probably is that of NaOH.
[20]H. W. Wolff, K. Radler, B. Sonntag, and R. Haensel, Z. Phys. 257, 353 (1972).
[21]J. A. D. Matthew and Y. Komninos, in Proceedings of the Interdisciplinary Conference on Surface Science, Warwick, England, 17–20 March 1975 (to be published).

Ion-Beam Implosion of Fusion Targets

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The performance of ion-beam–irradiated fusion targets consisting of a high-density spherical shell containing DT gas has been calculated. Breakeven with 10-MeV protons irradiating 1–2-mm-diam targets can be produced with a beam current around 10 MA. Results for various target sizes and other beam particles and voltages are also discussed.

Recently, serious attention has been given to several techniques of producing beams of high-energy ions that may be capable of producing thermonuclear fusion by imploding small targets similar to those suggested for laser and electron-beam fusion. Martin has proposed using a linear accelerator to produce a proton or helium beam with particle energies around 100 MeV, and then using several storage rings to compress the pulse length and increase the beam current.[1] Humphries, Lee, and Sudan have demonstrated that an electron-beam triode can produce an ion beam with relatively high efficiency.[2] Both of these techniques require further development to obtain the required power in one or more focusable beams, but there do not appear to be any fundamental obstacles.

Shearer has calculated ion-beam characteristics required to implode solid DT pellets and produce "scientific breakeven," where the thermonuclear yield equals the ion energy deposited in the target.[3] For the targets considered, breakeven required a rather precisely shaped pulse with a peak beam current around 4000 MA of 0.5-MeV deuterons and with a pulse width at the peak of about 0.1 nsec. As Shearer suggested, and as has been previously shown for electron-beam targets,[4] hollow-shell targets should substantially lower these beam requirements. This paper will show that the use of a high-density shell (e.g., gold) to absorb the beam energy and implode the fuel does indeed relax the beam requirements substantially, permitting the use of higher-voltage, lower-current beams (10 MeV, 10 MA or less) to achieve breakeven. The combination of higher beam voltages and lower temperatures (<1 keV) in the beam-absorption region largely eliminates the problem of range lengthening with increasing temperature encountered in bare DT pellets.

For electron-beam–fusion targets of this type, it has been found that the optimal performance is obtained when very little of the beam energy is deposited in the fuel or the interior portion of the metal shell.[4] For this reason targets are considered here which have shells thicker than the ions' range. Since the ions are scattered relatively little by the target material, and since the ion has a significantly higher energy loss rate near the end of its range, the metal shell can be divided conceptually into three regions: (1) an outer "tamper" layer where the beam-energy deposition is relatively low, (2) an intermediate "explosive" layer encompassing the end of the ions' range where the energy deposition is relatively high (the Bragg peak), and (3) an inner "pusher" layer which is unheated by the beam but which is imploded, compressing and heating the fuel to thermonuclear ignition. The tamper serves to contain the "explosion" of the explosive layer, providing a better conversion of its energy into pusher kinetic energy than is obtained in electron-beam or laser targets, wherein the energy is deposited in the outside ablator layer.

The computer code CLYDE[5] has been used to calculate the behavior of these targets. Except for the ion-beam energy deposition, the physics modeled in CLYDE is described elsewhere.[4,6] In these calculations the ions are assumed to be monoenergetic and to have trajectories directed toward the center of the target. In practice, departures from these assumptions will broaden the Bragg peak; a small amount of broadening will probably not significantly affect the target behavior.

Protons with energies greater than 1 MeV have a range-energy relation in gold given by[7]

$$E = 19x^{0.61},$$

where E is the proton energy in MeV and x is the range in grams per square centimeter. Since the protons traverse straight, radial lines, the energy deposited between two radii r_1 and r_2 is given by $19(x_2^{0.61} - x_1^{0.61})$, where

$$x = \int_{r_0}^{r} \rho(r)\,dr,$$

ρ is the density of the target material, and r_0 is the end point of the proton trajectory. Below 1 MeV, the above expressions are not accurate, and furthermore, the energy deposition is somewhat temperature dependent. However, the last 1 MeV of the proton's energy is deposited in 0.01 g/cm^2. Since this is barely within the resolution of these calculations, these effects do not appear to be significant here and are ignored. Similarly, the momentum of the beam protons is a small effect and is consequently ignored. In most of the methods of producing the ion beam, the beam current can be neutralized by low-energy electrons. Consequently, the effects of magnetic fields have been omitted from these calculations. If the beam current is not neutralized, the resultant magnetic field could alter the ion trajectories significantly. The neutralizing electrons would have at most a few percent of the ions' energy, and this would be deposited in the outer part of the tamper with little effect on the implosion. Both the beam current and the voltage are kept constant throughout these calculations. The product of the beam power and the implosion time gives an upper limit to the energy required for the implosion.

Calculations have been done for beams of different voltages (10 and 50 MeV), for shells of different sizes (1 and 2 mm inner shell diameter), and for various fuel masses, in order to show the trends in target behavior as these parameters are varied. The shell thickness is optimized for each beam voltage. For a 10-MeV proton beam the optimal gold-shell thickness is about 0.22 mm while for a 50-MeV beam the optimal thickness is 2.69 mm. In both cases there is about 0.1 g/cm^2 of gold which is unheated by the proton beam.

A fairly extensive set of calculations was done using a gold shell with an outside diameter of 1.44 mm and a thickness of 0.22 mm irradiated by 10-MeV protons. The thermonuclear energy produced with various masses of DT is shown in Fig. 1, plotted as a function of proton-beam current. Breakeven occurs for currents as low as 6 MA with 10 μg of DT. Similarity arguments, or dimensional considerations, indicate that the implosion time (time to attain maximum fuel compression) for a given target should be proportional to $P^{-1/3}$, and hence proportional to $I^{-1/3}$, where P and I are the beam power and current, respectively. Figure 2 shows the implosion times obtained from the calculations. As can be seen the scaling law is obeyed rather well, with the implosion times being essentially independent of the fuel mass, as is expected.

Figure 3 shows the ratio of initial to compressed DT volume as a function of the DT mass. This compression ratio is relatively independent of the proton-beam power, as would be expected if the implosion were purely hydrodynamic (no radiation, transport, etc.) Also shown in Fig. 3 is the beam current required for breakeven. Clearly, if the symmetry and stability of the implo-

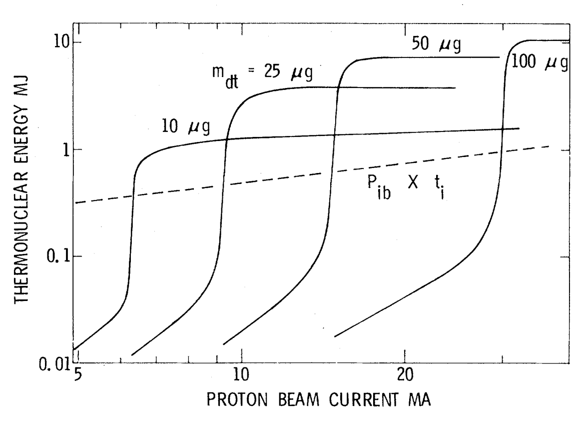

FIG. 1. Total thermonuclear energy produced as a function of proton-beam current for targets of various fuel masses (indicated on each curve). All targets have a 1.44-mm-outer-diam, 0.22-mm-thick gold shell. The dashed curve is the product of proton-beam power and implosion time, which is an upper limit on the beam energy required for the implosion.

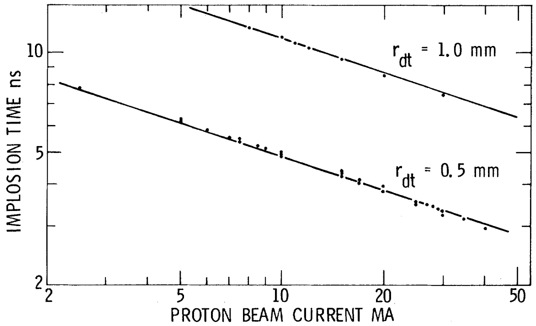

FIG. 2. Implosion time as a function of beam current for gold shells with 1.44 mm ($r_{DT}=0.5$ mm) and 2.44 mm ($r_{DT}=1.0$ mm) outer diameters. The gold-shell thickness is 0.22 mm in all cases. The straight lines are proportional to $I^{-1/3}$.

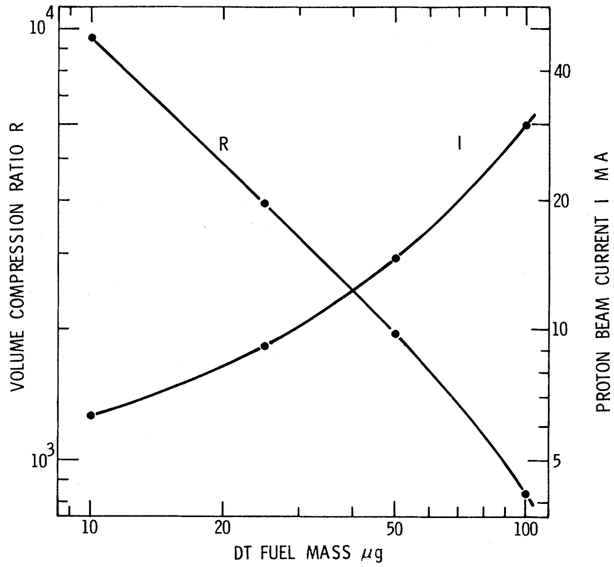

FIG. 3. Volume compression ratio and proton-beam current required to obtain thermonuclear ignition (breakeven) as a function of DT fuel mass for targets with a 1.44-mm-outer-diam, 0.22-mm-thick gold shell.

sion is not good enough to obtain compression ratios of 10^4, somewhat higher beam currents, 10–20 MA, will be required.

A series of calculations has also been performed with a larger gold shell, 2.44 mm outer diameter, 0.22 mm thick, filled with 100 μg of DT. Breakeven requires slightly more than 11 MA of 10-MeV protons with this target. The compression ratio is about 5×10^3 and the implosion time is about 10.5 nsec.

The results of these calculations can be readily extended to higher voltages: By adding an additional layer of gold to the outside of a 10-MeV target, so that the end point of the proton range is the same distance (~0.1 g/cm^2) from the inner surface of the pusher, the behavior of the target should be nearly the same as for the 10-MeV target for the same beam *current.* Calculations with 50-MeV protons have borne this out. For a target with a 6.38-mm-diam shell, 2.69 mm thick, filled with 50 μg of DT, the behavior was very similar to the target filled with 50 μg of DT shown in Figs. 1–3. For example, the current required for breakeven is about $15\frac{1}{2}$ MA. Of course, 5 times more power is required at 50 MeV, but in some cases these high currents may be easier to produce at the higher voltage. One might expect that the results could also be extended to lower voltages by reducing the thickness of the shell. However, if too much material is removed, the outer part of the shell loses its effectiveness as a tamper. This probably occurs when the tamper mass becomes less than the pusher mass below 5–7 MeV, although calculations have not yet been done to check this.

The results given above for 10-MeV protons apply equally well to 40-MeV α-particle and 13-MeV deuteron beams of the same power ($\frac{1}{2}$ and $\frac{3}{4}$ the current, respectively) since the ranges of these particles are the same as that of a 10-MeV proton. Similarly the 50-MeV-proton results apply to 200-MeV α's and 67-MeV deuterons. The targets discussed here for 10-MeV protons are quite similar to targets discussed previously for 1-MeV electron beams.[4] With the proton beam, breakeven is obtained with a power as low as 60 TW, whereas with electron beams, 800 TW is required. By using a lower-atomic-number ablator to reduce the preheating of the pusher inner surface by beam-produced bremsstrahlung, the electron-beam power required for breakeven can be reduced by at least a factor of 2.[8] (Such a technique is of no use in ion-beam targets since the ions produce no significant radiation.[9]) The remaining factor-of-6 difference in performance of electron- and ion-beam targets is evidently due to the advantageous fashion in which the ions deposit their energy.

Kirkpatrick *et al.* have shown that the power required for thermonuclear ignition in targets of this type can be halved by using a concentric inner metal shell to achieve velocity multiplication.[10] Further stages of velocity multiplication may reduce the power requirement even further. In electron-beam targets of this type, the beam-produced bremsstrahlung causes the inner shells to expand before velocity multiplication occurs, reducing their effectiveness somewhat.[11] This does not seem to be a problem for ion-beam-driven targets.

As has been shown, ion-beam currents of 10 MA or less are required to achieve breakeven. These are considerably lower than the electron-beam currents required for similar targets. Electron currents in excess of 1 MA at 14 MeV have been produced[12] (but with too long a pulse length). However the ion-beam current densities achieved to date in this relatively new field are orders of magnitude below the electron-beam current densities that have been achieved. Further work, presently underway in several laboratories, is needed in order to understand the production and focusing of intense ion beams before ion-beam fusion can be compared quantitatively with other approaches to fusion.

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[1]R. L. Martin, Bull. Am. Phys. Soc. 20, 209 (1975), and IEEE Trans. Nucl. Sci. 22, 1763 (1975).

[2]S. Humphries, J. J. Lee, and R. N. Sudan, Appl. Phys. Lett. 25, 20 (1974), and J. Appl. Phys. 46, 187 (1975).

[3]J. W. Shearer, Lawrence Livermore Laboratory Report No. UCRL-76519 (to be published).

[4]M. J. Clauser, Phys. Rev. Lett. 34, 570 (1975).

[5]B. D. Meixner, unpublished; H. Smith, unpublished.

[6]A very similar hydrocode was used in the work of G. S. Fraley, E. J. Linnebur, R. J. Mason, and R. L. Morse, Phys. Fluids 17, 474 (1974).

[7]W. Whaling, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1958), Vol. 34, p. 193; W. H. Barkas and M. J. Berger, in *Studies in Penetration of Charged Particles in Matter*, Nuclear Science Series, Report No. 39 (National Academy of Sciences—National Research Council, Washington, D. C., 1964), p. 103.

[8]M. A. Sweeney and M. J. Clauser, Appl. Phys. Lett. (to be published).

[9]E. Merzbacher and H. W. Lewis, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1958), Vol. 34, p. 166.

[10]R. C. Kirkpatrick, C. C. Cremer, L. C. Madsen, H. H. Rogers, and R. S. Cooper, Nucl. Fusion 15, 333 (1975).

[11]J. Nuckolls, R. Thiessen, and R. Bangerter, private communication.

[12]B. Bernstein and I. Smith, IEEE Trans. Nucl. Sci. 20, No. 3, 294 (1973).

Interaction of Relativistic Electron Beams with Fusion-Target Blowoff Plasmas

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The relativistic Boltzmann equation with a Fokker-Planck collision term is solved assuming that elastic scattering characterizes the shortest time scale of the beam-plasma system. One-dimensional solutions containing the self-consistent return-current electric field show that, although range shortening occurs, the electric field prevents high-current-density beams from penetrating into the dense-plasma region.

The goal of relativistic electron-beam-initiated fusion reactions in targets containing a deuterium-tritium mixture[1,2] has prompted theoretical interest in the interaction between the beam and a plasma blown off of a high-atomic-number shell surrounding the fusionable material. Investigations have included collisional scattering and energy loss of the beam due to plasma in the absence of electromagnetic fields,[3,4] while others have discussed effects due to these fields neglecting the self-consistent collisional interaction.[1,5] Here, a theory for beam deposition including both collisional and field effects is presented. The relativistic Boltzmann equation with a Fokker-Planck collision term is solved assuming that the elastic-scattering collision time scale is the shortest of the system. A one-dimensional solution is obtained which includes the electric field generated by the plasma return current. The energy transfer from beam to plasma is estimated for this solution and the constraints placed on beams for fusion applications are discussed.

The equation describing the momentum distribution function of relativistic electrons interact-