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Report of the Heavy-Ion Fusion Task Group

University of California

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REPORT OF THE HEAVY-ION FUSION TASK GROUP

by

G. A. Sawyer, Chairman; L. A. Booth, D. B. Henderson, R. A. Jameson,
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ABSTRACT

An assessment of heavy-ion fusion has been completed. Energetic heavy ions, for example 10-GeV Uranium, provided by an rf linac or an induction linac, are used as alternatives to laser light to drive inertial confinement fusion pellets. The assessment has covered accelerator technology, transport of heavy-ion beams, target interaction physics, civilian power issues, and military applications. It is concluded that particle accelerators promise to be efficient pellet drivers, but that there are formidable technical problems to be solved. It is recommended that a moderate level research program on heavy-ion fusion be pursued and that LASL should continue to work on critical issues in accelerator development, beam transport, reactor systems studies, and target physics over the next few years.

I. INTRODUCTION

The Heavy-Ion Fusion (HIF) Task Group met 20 times over a 3-month period. We had visits from Roger Bangerter (LLL), Glenn Kuswa (Sandia), Bill Herrmannsfeldt (SLAC), Al Maschke (BNL), Denis Keefe (LBL) and Hermann Grunder (LBL). We have also made visits to Argonne National Laboratory, Sandia Laboratory, and Lawrence Berkeley Laboratory.

There was a two-week HIF Workshop at Berkeley (Oct. 29-Nov. 9, 1979) with international participation of nearly all the principal workers in HIF. The Workshop concentrated on critical problems for HIF; its conclusions, summarized in Section II and elaborated on in Section III, provide the best available information on many technical issues associated with accelerators.

The principal laboratories now working on the two main approaches to HIF accelerator drivers are Argonne National Laboratory and Lawrence Berkeley Laboratory. Argonne is investigating some aspects of the rf-linac approach and Berkeley is concentrating on the linear-induction approach. Test-bed experiments in the $25-50M range have been proposed by both laboratories and are under construction as funding permits. Brookhaven National Laboratory has also been active in the rf-linac approach. Almost all of the target design to date has been done by R. Bangerter of LLL. Issues involved in beam propagation, target interaction, and applications of HIF to commercial power and military research, are discussed in Sections IV-VII.

Justification for Heavy Ion Fusion

We believe that fusion power development is a valid national priority. HIF should be pursued as a promising advanced driver option for inertial confinement fusion. The proper pace of the HIF program is unresolved.

Theoretical requirements of pellets for ICF reactors are becoming better established. It is necessary to deposit at least 20 MJ/g in the target. Target pellets have a radius of a few millimeters determined by compromise between pellet gain, minimum pellet mass, driver energy, and practical limits on beam focus. These requirements lead to the conclusion that the driver energy must be 1-10 MJ with peak power of about 100 TW. Such large driver energy will be difficult to achieve with lasers.

However, it is currently believed that heavy-ion drivers will have high efficiency and that the necessary driver energy (1-10 MJ) will be easier to achieve with heavy ions than with lasers. The key target questions appear to be the maintenance of the focused beam in the target material and the energy deposition processes. It is believed that the beam-target interactions will be classical; at least convincing counter arguments have not been developed. The DOE review committee on inertial fusion chaired by John Foster could identify no apparent flaw in the heavy-ion driven ICF reactor. We are unsure of the extent to which this is a "greener grass" effect.

Particle accelerator systems can probably be developed to accelerate 10-MJ bunches of 10-GeV heavy ions. The systems will be very large and expensive, but possibly cheaper than equivalent energy laser drivers although not as cheap as light ion systems presently envisioned. Two main heavy-ion accelerator systems are being considered: 1) the rf linac with storage rings for current multiplication, and 2) a single-pass linear induction accelerator. The rf approach involves less extrapolation of existing accelerator technology than the induction accelerator approach; experience with induction accelerators is limited to electrons.

There are real military applications of all inertial confinement fusion approaches. The Task Group believes that a $30M/year effort on HIF can be justified because of its potential military applications, but it is not reasonable to build a demonstration experiment at a cost of a few-hundred-million dollars solely on the basis of military applications. Some military application experiments of interest can be conducted using laser facilities already under construction (e.g. NOVA, ANTARES). Expensive new drivers and a crash program to demonstration power plants for ICF _must_, however, be justified solely for civilian power applications.

Problems for Heavy-Ion Fusion

Beam quality and final transport are certainly the biggest unknowns in HIF. In both accelerator systems there are serious hurdles to be overcome in order to deliver the required energy with the necessary beam quality. In simplest terms, can the beam be bunched to a length of 10 ns and focused to a radius of 2.5 mm? Defocusing by current variations along a bunch and beam instabilities during final transport of the beam to the target are problems. Other problems arise from aberrations and instabilities in the accelerator system that degrade the beam emittance. Critical components that require development for the rf approach are the ion source and low-beta accelerator, the storage ring, and the final beam bunching and transport. No operational experience is available for ion acceleration with induction linacs; thus problem areas are largely undefined in detail, but generally involve questions of collective instabilities in the long "sausage" of beam, and on the tolerances required in the voltage waveform.

In the area of target interactions, the available information indicates that absorption of beam energy in the target is straightforward, compared to lasers, and can be calculated. There are, however, no data with intense heavy-ion beams or with hot dense stopping material. There are large extrapolations involved. Heavy-Ion Fusion offers no panacea for present uncertainties in energy conversion and implosion physics. Considerable effort is needed on detailed target designs and in the study of interaction physics. Unfortunately, large, high-energy, expensive systems are required to explore target phenomena experimentally. A 100-kJ Heavy-Ion Demonstration Experiment (HIDE), sufficient to do extensive target interaction and implosion experiments, will be relatively very expensive, probably more than one-hundred-million dollars. High development costs are a real problem for HIF.

Schedule for HIF

Considering the uncertainties of target gain, interaction physics, and driver energy, the potential for any ICF driver option at the present time is uncertain. Therefore, choices between potential ICF driver options should await further studies.

In view of the many uncertainties in HIF, there is no justification for a HIDE in the next few years. The Task Group feels that, for the next two or three years, a theoretical and experimental program studying areas of concern with respect to the accelerator driver is warranted at a funding level of $15-30M per year. The program should concentrate on answering critical questions in HIF in order to make a technically-based choice between rf-linac and linear-induction accelerators possible by FY84 or 85.

The program over the next 5 years should include construction of the proposed test-bed experiments at ANL and LBL and supporting studies at other laboratories. Favorable clarification of the accelerator issues in these efforts would justify considering the options for construction of a 100-kJ HIDE starting in FY85.

In addition, however, it is important to obtain the earliest possible target interaction data. It would be desirable to construct a 10-kJ target facility starting in FY82. The facility would be used for target interaction studies and further accelerator development. To keep the expense down while satisfying the target study requirement, a pulsed, low-duty-factor machine could be considered.

Management of HIF Program

LASL has accepted a lead-laboratory role for the rf-linac approach to HIF. Initially, our main management responsibility will be to oversee the Argonne program. Argonne has excellent physical facilities for a heavy-ion test bed (including a storage ring tunnel) and a few competent senior staff to carry out a program. The Task Group believes that Argonne should be encouraged and supported in carrying out initial experimental research. We are pleased that Argonne has modified their proposal which originally was to build a complete engineering prototype facility and are moving in the direction of a research program to answer critical accelerator questions.

We have discussed the management role of LASL in the rf-linac approach and recommend that a technical steering committee be formed. The first item of business for this committee is to develop a detailed program plan, to be submitted to DOE, which would outline the optimum HIF experiments and studies using existing resources, as well as define a longer-term program to address the full technical feasibility of HIF. We feel it is desirable that such a committee have jurisdiction over both the rf and induction linac HIF driver approaches, with appropriate representation from LASL, ANL, LLL, BNL, Sandia, DOE, presently active laboratories, and possibly others.

Until a detailed program plan has been developed, management of the HIF rf-linac approach by LASL will consist mainly of overseeing on-going activities, consistent with current funding levels. Hence, for the near-term, no large departures from current HIF activities are foreseen.

LASL Role in HIF

We believe that HIF is a high-risk program. It would not be prudent for LASL to take on a large in-house program now, although LASL has the expertise to do so. LASL should have a selective involvement, concentrating its research effort in areas where it already has existing skills and related programs. Work on the application of the RF quadrupole to heavy ions should continue. Theoretical effort on target design, target interaction physics and high-current beam transport should be extended. A reactor system study should be carried out, and effort should be applied to the theory of emittance growth.

II. BERKELEY HEAVY-ION WORKSHOP - OCT. 29 - NOV. 9, 1979

At the Berkeley Heavy-Ion Fusion Workshop, no fatal flaw was discovered to prevent continued development of heavy-ion drivers for inertial confinement fusion. However, increasingly sophisticated HIF theoretical studies are revealing definite problem areas to be worked on.

Following are a few highlights from each working group at the conference:

Target Requirements

Target considerations are suggesting that the particle energy should be equivalent to a 5-GeV uranium atom, a considerably lower kinetic energy than the accelerator people would like to work with. At the end of the conference, however, it was agreed that good compromise reference parameters for use over the next year would be total beam energy 3MJ, uranium particle kinetic energy 10 GeV, spot radius 2-1/2 mm, 10 ns pulse.

Transport in the Reactor Chamber

There are a number of beam-plasma instabilities that may cause trouble if the beam is propagated through a gas to the target. If the particle kinetic energy goes down to 5 GeV, a postulated "window" for transmission between 10^{-1} torr and 10^{1} torr will disappear but there may still be an upper pressure limit at 10^{-3}-10^{-4} torr where the two-stream instability is not too serious. Propagation in a high vacuum would be straightforward to calculate, but space charge effects force the number of beams to be large.

Transport in the Final Beam Line

Variations in the space charge in a beam bunch will cause changes in the effective focal length of the focusing magnets. An analysis has not yet been made to determine to what extent this is a problem, or to determine what corrective elements are required in the transport line.

Storage Ring

The longitudinal microwave mode, an instability associated with resistive coupling of the beam to the walls of the beam vacuum chamber, is serious. Detailed calculations are lacking, but it is certain to limit the beam to low charge states, possibly as low as +1. It may be possible to conduct early experimental tests to establish operational limits for this instability with low-energy heavy ions at Argonne or in existing proton machines. Intra-beam charge exchange and scattering of ions on background gas are also problems. Beam losses to the wall, and during injection and ejection, must be kept small to prevent wall sputtering or out-gasing leading to further beam scattering, a positive feedback condition.

Main Accelerator

There are some problem areas, especially with induction linacs for which detailed theoretical analyses are lacking. However, it is believed that the performance of rf linacs can be reliably calculated and that no serious concerns exist for this approach.

Low-Beta Accelerator

The main concern with the low-beta accelerator is validation of the calculations on techniques to restrict the growth of emittance and capture the beam in succeeding stages. A number of options exist for the preaccelerator in the rf-linac approach. For the induction linac, low-beta acceleration remains to be demonstrated.

Conclusions

There was a fairly general agreement that more computer simulations should be made to predict beam behavior. It was also agreed that the planned experimental test beds at Argonne and Berkeley should be used where possible to test the beam instability problems at low power. By using appropriate scaling laws, these results may be useful to evaluate concerns for high-intensity accelerator concepts.

III. ACCELERATOR ISSUES

The recent Heavy-Ion Fusion Workshop held at Berkeley was convened to study only those issues associated with the feasibility of constructing a heavy-ion accelerator capable of driving an inertial confinement fusion target for power production. The general conclusion, as stated above, was that the development of such an accelerator appeared to be possible, with no insurmountable difficulties. There were, however, several areas of concern which were defined more sharply than previously, as a result of the deliberations at this Workshop.

Present "Test Bed" Activities

In view of the persisting concerns, it seems inadvisable at the present time to proceed from the present technology base to a HIDE without an intermediate step which would allow for research and development of as many of the areas of concern as possible, including studies in heavy-ion target physics. In this context, it is unfortunate that the Workshop did not consider the existing "test bed" designs; a "500-joule" Linear Induction Accelerator at LBL and the Argonne "50-joule" Phase 0 project. No guidance resulted from the Workshop on the ability of these test beds to resolve accelerator issues of concern; hence, the burden of these assessments rests with the respective lead laboratories (LASL, in the case of the Argonne project). In order to achieve a balanced judgment of the ultimate effectiveness of the Argonne Phase 0 program, it is important that the LASL-proposed Technical Steering Committee review the Argonne program in the process of developing a detailed program plan.

Beam Dynamics Analyses

One of the conclusions of the Workshop was that, up to now, adequate beam dynamics analyses are lacking. Emittance growths and realistic current limitations of the various accelerator sections have not been determined quantitatively. Appropriate computer-based simulations for the low-beta and rf-linac sections of the accelerators under development or proposed need to be made, and are possible. While there seems to be no reason to suspect that these sections of a high-intensity heavy-ion accelerator pose serious problems to the development of a driver facility, there is a paucity of quantitative analysis confirming the largely intuitive or qualitative statements made up to now on the performance characteristics of the low-beta and rf-linac sections. Of course, experimental confirmation of the analyses is needed, but it is not yet clear that the proposed test beds will provide the needed validation.

In the rf-linac approach, most of the concern unique to this approach centers about the possible instabilities and beam losses associated with the use of a storage ring. More study is apparently needed to determine how much can be learned from a "small" facility which can then be scaled to heavy-ion driver proportion. Some questions, such as the tolerable beam loss to the vacuum chamber and septa, may not be answerable until the HIDE stage of development. Also, certain of the beam instabilities may remain questionable until a HIDE is available.

LASL Accelerator Developments

At the present time, LASL has an effort in the development of one of the low-beta accelerator options. Our work on the Radio Frequency Quadrupole (RFQ) accelerator is relevant to the developments needed for a heavy-ion driver. This low-beta design seems to embody the design criteria needed for high efficiency and high brightness in order to meet the storage ring input requirements. In order to confirm our analysis of this design, it would be highly appropriate to construct a functional RFQ for heavy ions as a continuation of the present design effort.

IV. BEAM PROPAGATION

Introduction

In current development of a heavy-ion fusion conceptual design, a major concern for heavy-ion fusion is to define the minimum number of beams to deposit the required energy on target. An answer to this concern depends on the outcome of studies of stable propagation and focusing of an intense beam to a small target. Since the inception of heavy-ion drivers approximately four years ago, three modes of propagation for heavy ion beams have been suggested and investigated in some detail: ballistic propagation, self-focused propagation, and preformed channel propagation. Recently, ballistic neutralized beam propagation has also been suggested.

Ballistic Propagation

Because of the smaller current requirements compared to light ions, heavy-ion ballistic propagation in vacuum (for which much experience is extant) provides an approach for which no new concepts need to be developed. If the pressure in the reactor chamber is less than about 5×10^{-4} torr, the mean free path for ionization is long compared to the standoff distance. Under these conditions, the spot size of the beam is limited by a combination of space-charge variations and aberrations associated with the beam velocity distribution and the final focusing lens. Assuming beams of high quality a sufficiently small spot size can always be achieved by increasing the number of beams. As the chamber pressure is increased several problems arise. Plasma production and stripping quickly lower the probability of achieving a ballistic focus. The achievable spot size is limited by shot-to-shot variation in focal length of the lenses caused by variation in background gas pressure. The presence of microinstabilities further complicates the magnetic deflection problem. Filamentation instabilities are electromagnetic and can cause direct modification of the self-magnetic field profile. The two-stream instability is electrostatic but can modify the local plasma conductivity significantly, and thus indirectly the beam self-magnetic field. Knock-on electrons generated at the beam head also add another unknown in the magnetic deflection problem.

Self-Focused Propagation

For the self-focused mode of propagation, the reactor chamber pressure is considered to be greater than 5 torr and the beam radius in transport is about equal to the target size. This implies that the ion beam is prefocused in the final beamline vacuum or in the reactor chamber. Expansion and erosion of the beam head occurs as the beam traverses initially neutral gas in the target chamber, leading to some energy loss by the beam. Behind the beam head, complete charge neutralization and partial current neutralization occurs. The residual self-magnetic field of the beam balanced against the beam internal pressure leads to an equilibrium radius of the beam which, unfortunately, depends sensitively on the plasma conductivity. The stray ions associated with beam-head expansion could cause preheat problems for certain classes of targets. Additionally, beam-head erosion and heating of the plasma channel both cause power profile modifications.

Preformed Channel Propagation

In the preformed channel mode of propagation, being studied at Sandia and NRL for light ions, an azimuthal self-magnetic field of a preformed current channel is balanced against the beam internal pressure to provide equilibrium for propagation through a reactor chamber at gas pressures greater than 5 torr. This mode also requires prefocusing of the ion beam but now proper matching of the beam to the channel must be considered. Questions arise, moreover, concerning the channel stability. Finally, since the channel is heated as the beam propagates through it, as with the self-focused mode of propagation, significant beam energy loss and power profile modification could occur during transport.

Status of Propagation Physics

Presently, there exist too many unknowns in terms of accelerator technology, target requirements, and atomic physics to make any reliable assessment of high-pressure ballistic focus, self-focus, or preformed channel propagation modes. In the presently favored reactor concepts, propagation in the reactor takes place at approximately 10^{-3} to 10^{-4} torr in which the mean free path for ionization is long compared with the standoff distance. To zero order, this is essentially ballistic propagation in vacuum. Unfortunately, target studies now indicate that the preferred kinetic energy for heavy-ion fusion drivers is 10-GeV uranium ions, much less than originally suggested. At the same time, the total energy requirements have been steadily increasing. The net result is that the space-charge limits on spot size for ballistic propagation now require a large number of beams on target, even for heavy ions. As target and accelerator requirements become more well defined, additional work should be carried out on plasma propagation, i.e., above 10^{-3} torr.

Conclusions

Because recent developments in target requirements favor lower beam kinetic energy and higher beam current, an increasing number of beams is implied to avoid space charge. A propagation mode that can possibly allieviate the imposed space-charge limits is low-pressure neutralized beam propagation. This mode is being studied for light-ion drivers, for example the TRW LIFE and Sandia PULSELAC concepts. Considering the uncertainties in the choice of ion driver and target, neutralized beam propagation in vacuum should be investigated for possible future consideration. Subjects for study are the position and technique of the neutralization itself, the effect of internal electron pressure on spot size, the effect of local inhomogeneities, and the presence of possible instabilities due to velocity anisotropy in the neutralizing electron stream.

V. TARGET INTERACTIONS

Introduction

In this section the status of heavy-ion target design and the associated interaction physics are discussed. One-dimensional heavy-ion designs appear fairly attractive; however, symmetry and particle ranges in hot materials are critical considerations. Included in the discussion are the present understanding of heavy-ion ranges along with comparisons to the ranges of hot electrons resulting from CO_2 laser plasma interactions. The particle ranges determine the energy density in the target material. Any uncertainty about them translates directly into uncertainty in the energy deposition levels required to make heavy-ion fusion work. A more complete discussion has been communicated to the Task Group.[1]

Target Design

The simplest targets are metal microballoons filled with DT fuel. More complicated designs are shown in Fig. 1. These designs can be characterized as colliding shell targets and simple ablator-pusher-fuel designs. The Polaris (LASL) and similar LLL designs are colliding-shell designs employing velocity multiplication. These designs and their double-fueled variants require little driver pulse shaping because the target structure (cushion) provides effective shaping. More conservative designs require more mass in order to have the structure provide the shaping, and they correspondingly produce lower gains than do the no-collision designs. There is a trade-off between driver pulse shaping and the complexity of target design. All of these design concepts are shared with laser fusion and inertial confinement fusion generally.

Simple Targets

Representative of simple microballoon designs are those described by Keith Brueckner and Nathan Metzler (private communication, 1979), which are thin shells of aluminum with frozen hollow layers of DT. Using time-shaped

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[1] D. B. Henderson and J. M. Kindel, "Interaction of Heavy-Ions with Inertial Confinement Fusion Targets (U)", , Los Alamos Scientific Laboratory report LA-8208-MS (SRD) (January 1980).

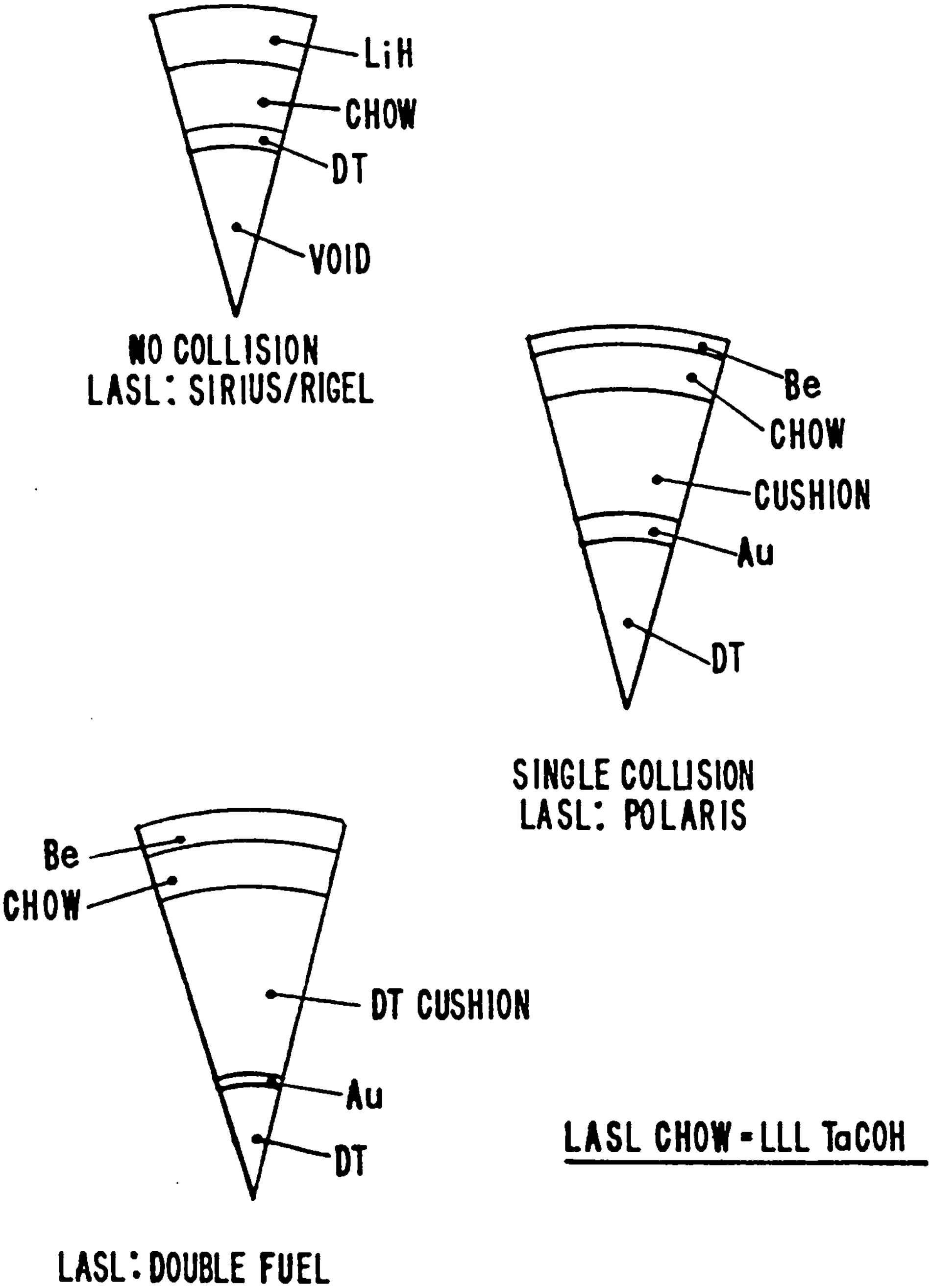

Fig. 1. Categories of ICF targets. Similar configurations have been developed at Livermore. CHOW is a high-Z impregnated plastic.

pulses, the gains calculated are tabulated below, along with corresponding results from somewhat more realistic calculations at LASL, for three ion species:

Shell Radius (mm)	Shell Radius:Thickness	Energy Input (kJ)	Target Gain	LASL Target Gain		
				Xe	Hg	U
0.5	33:1	20	20	0.11	0.10	0.08
1.0	33:1	62	74	53	30	1.8
2.5	33:1	401	295	281	250	60
2.0	17:1	403	294	230	224	204

The above results are illustrative of much of the optimistic thinking in the field. Assumptions used include perfect gas equations of state, full ionization, no radiation losses, and local alpha-particle energy deposition. Relaxing the assumptions degrades the results by many orders of magnitude. The original calculations used uniform, constant deposition of the heavy-ion energy; a table of equivalent particle kinetic energies for the three ions Xe, Hg, and U was provided. The LASL calculations differed by including the deposition physics for each ion at the given equivalent kinetic energy. Because the depositions are neither uniform nor constant in time, the results vary as shown. It should be noted that increased realism (more physics) makes the results more variable and less optimistic.

A further difficulty is that the simple targets function by forming very thin effective pushers from the inner edge of the aluminum shell, compressing this thin layer to densities of a few thousand g/cm^2 and typically 10 μm thickness. The resultant gain is dependent on the one-dimensional calculation and on the unrealistic condition that the pusher layer is cold, while the ablative layer is hot (both layers come from the same shell).

More realistic, near-term targets consisting of gold microballoons with DT gas fuel are being designed at LASL in conjunction with the Argonne program. We have recently obtained a gain of 14 at 3 MJ deposited energy with a simple unoptimized target.

Complex Targets

Ion-beam target designs to be used with pulse shaping have been developed at LASL, and published recently.[2] The original motivation was to use laser-produced ions to drive a target. These designs, which idealistically employ a monoenergetic ion beam appropriate for light ions, are similar to those of Fig. 1. Typical target calculation results are shown in Fig. 2, for the target design shown, where CHOW (LASL) - TaCHO (LLL) is a high-Z impregnated plastic. The pulse shaping shown in Fig. 2b is very modest compared to many of the shaped pulses in inertial fusion; however, the yield ratios produced are correspondingly more modest. The assumed range of the incident ion is only 3 mg/cm^2; the prepulse power peaks at 2.9 TW, while the main pulse peaks at 260 TW.

Classified Targets

The classified approaches are discussed in a separate document.[1] The designs have been developed for heavy-ion fusion by Roger Bangerter at LLL. (Livermore dominates this subfield, having the only funding for heavy-ion fusion target design until recently.)

The Question of Ranges

Crucial to heavy-ion designs is the serious question of ranges in hot materials. The question involves both the overall range and the spatial deposition profile. Sensitivity to the profile is illustrated by the variance of results for the simple targets already discussed. The particle ranges must, of course, be compared with other length scales in the target design: x-ray mean free paths for preheat considerations, electron mean free paths for preheat, and material thicknesses for realistic temperatures or energy densities. The direct impact of the scale of particle range is that, in order to take advantage of the range (especially to utilize the Bragg energy deposition peak), the amount of material in the target must correspond to the particle range. For longer ranges, as more material is heated, the total energy deposition requirement must go up. Additionally, uncertainties in the ranges used for design result in uncertainties in total energy requirements.

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[2] J. M. Kindel and E. L. Lindman, "Target Designs for Energetic Ions," Nuc. Fusion, 19 5 (1979).

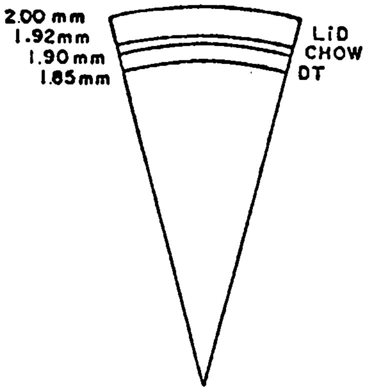

Fig. 2a. Ion-driven target appropriate for 1 MJ of input energy. Yield ratio is 90 for pulse shape below.

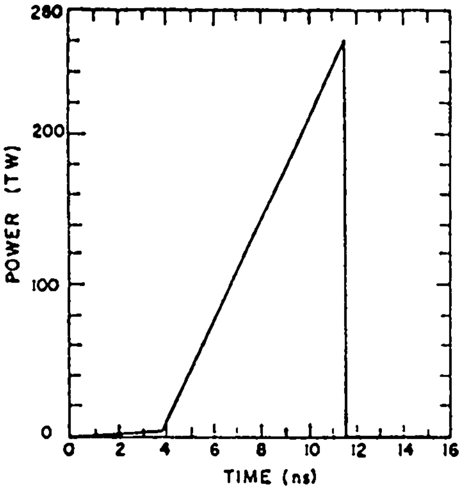

Fig. 2b. Power as a function of time delivered by a monoenergetic ion beam with range of 3 mg/cm^2.

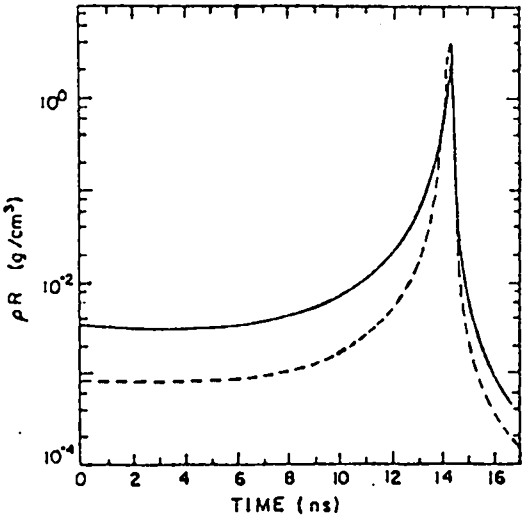

Fig. 2c. The ρR of the CHOW plus fuel (upper curve) and the fuel itself as functions of time.

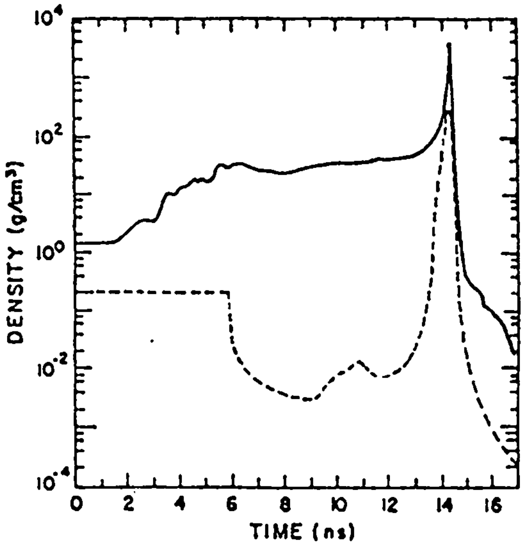

Fig. 2d. Maximum density in the target (upper curve) and density of the inner zone of fuel as functions of time.

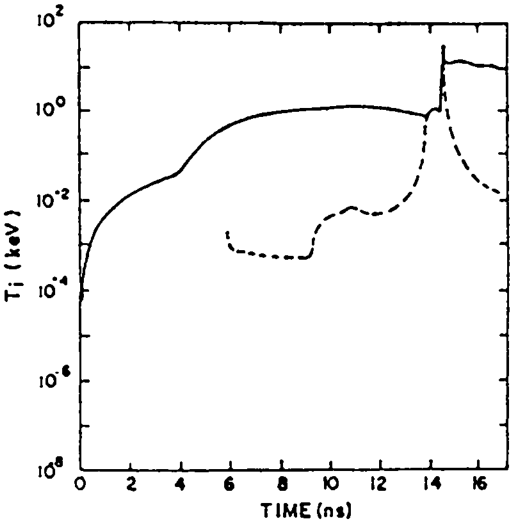

Fig. 2e. Maximum ion temperature in the target (upper curve) and the ion temperature in the inner zone of fuel as functions of time.

No data exist for the deposition of energy from intense ion beams or for deposition into hot material. The calculated intense ion beam depositions into hot material are therefore extrapolations based on data for single particles in cold material. Tom Mehlhorn at Sandia has carried out calculations for both light and heavy ions to address the differences between deposition in cold and hot material. Figure 3 summarizes the results for heavy-ion deposition in cold and hot material. The range curves shown in Fig. 3 are for two arbitrary target conditions; the actual interaction embodies a transition from one physical condition to another. Figure 3a shows the range in g/cm^2 as a function of energy for U, Hg and Xe ions being deposited in (normal density) cold gold. Note that for the heavy-ion kinetic energies of interest, 5 to 10 GeV, the cold ranges are 100 to 200 mg/cm^2. Figure 3b shows results for the same calculation except the gold is now at 200 eV and one-hundredth normal density. For these conditions, the ranges for 5- to 10-GeV ions are shortened by almost a factor of two. Because range is such an important parameter in terms of the efficiency at which we can drive an implosion, it is worthwhile to compare these ranges with ranges appropriate to other drivers, i.e., with those of light ions having practical kinetic energies and laser-generated hot electrons. In Fig. 4, calculations by Mehlhorn are shown for light-ion range versus ion kinetic energy for deposition into gold for the same target conditions as for Fig. 3. Two points worth noting are that these ranges are one order of magnitude less than those for heavy ions, and the reduction in ranges from cold to hot target material is again almost a factor of two. Recent range considerations have driven the heavy-ion beam kinetic energy requirement downward, even below 5 GeV; it is clear, then, that the short ranges of light ions can be advantageous.

It is also instructive to compare these ranges with those of energetic electrons which arise in laser fusion. In Fig. 5, results of Jack Comly at LASL are presented which show the deposited specific energy as a function of depth for a one-dimensional 60-keV Maxwellian electron distribution in gold. This temperature is chosen to be at the upper end of expected hot-electron temperatures in CO_2 laser-produced plasmas. If we wish to obtain a realistic range which eliminates preheat, then a choice of 20 m is reasonable. This corresponds to roughly 40 mg/cm^2, as compared with 100 to 200 mg/cm^2 for heavy ions. It should be noted that, for the longer wavelength lasers, e.g. CO_2, nearly all the absorbed energy appears as superthermal electrons

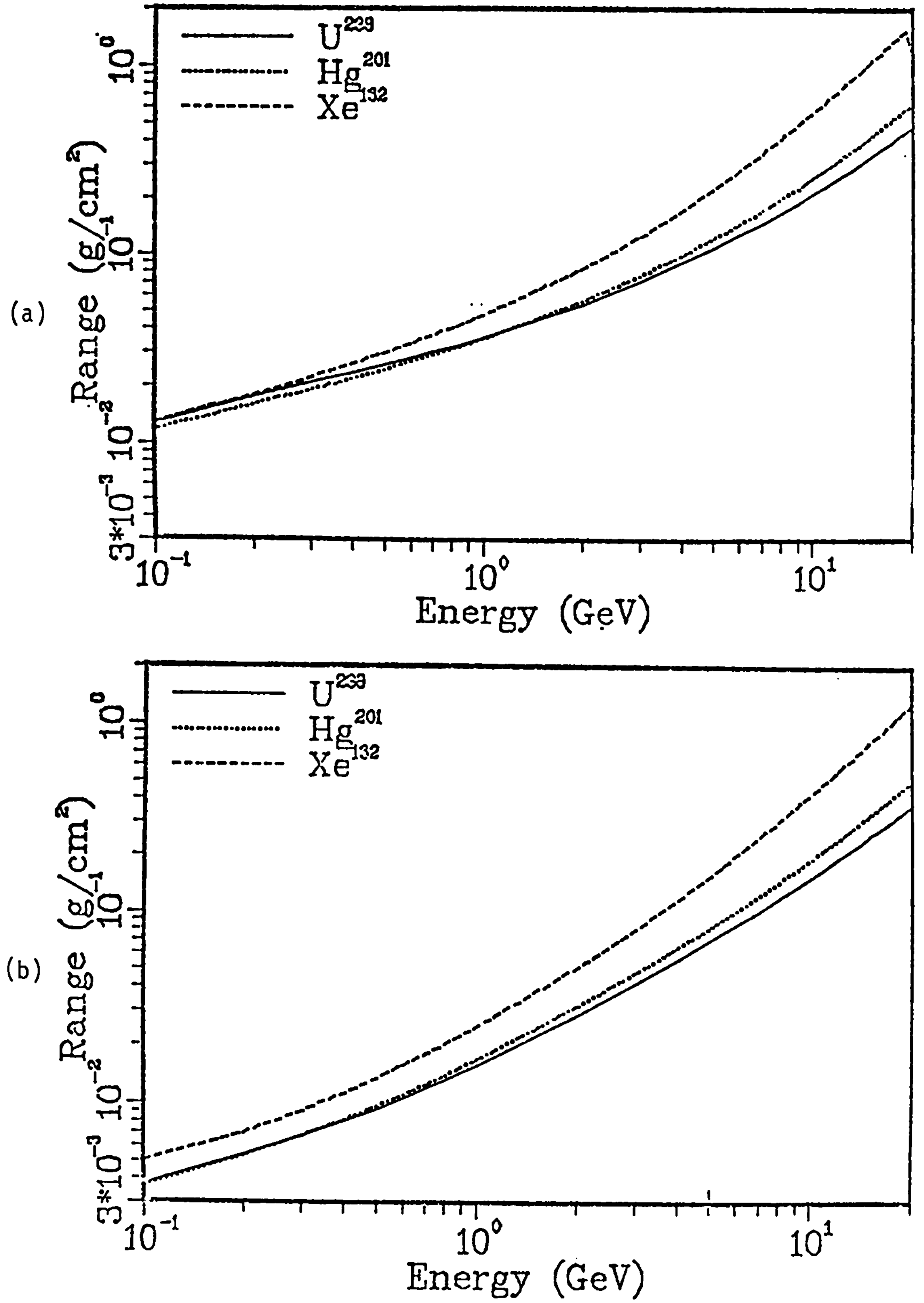

Fig. 3. Calculated heavy-ion ranges in gold.

(a) Cold (T=0 eV), normal density material.
(b) Hot (T=200 eV), one-hundredth normal density material.

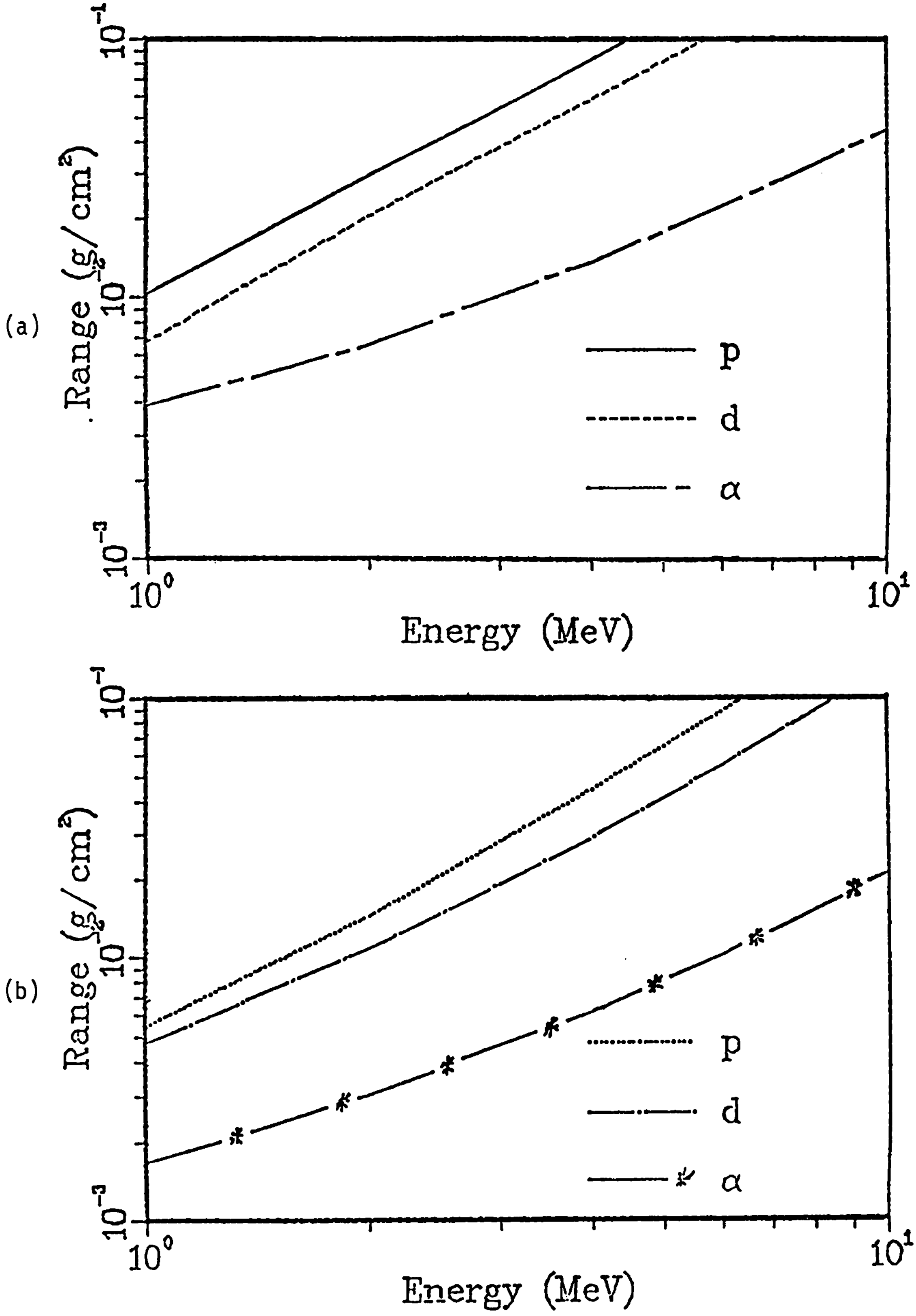

Fig. 4. Calculated light-ion ranges in gold.

(a) Cold (T=0 eV), normal density material.
(b) Hot (T=150 eV), one-hundredth normal density material.

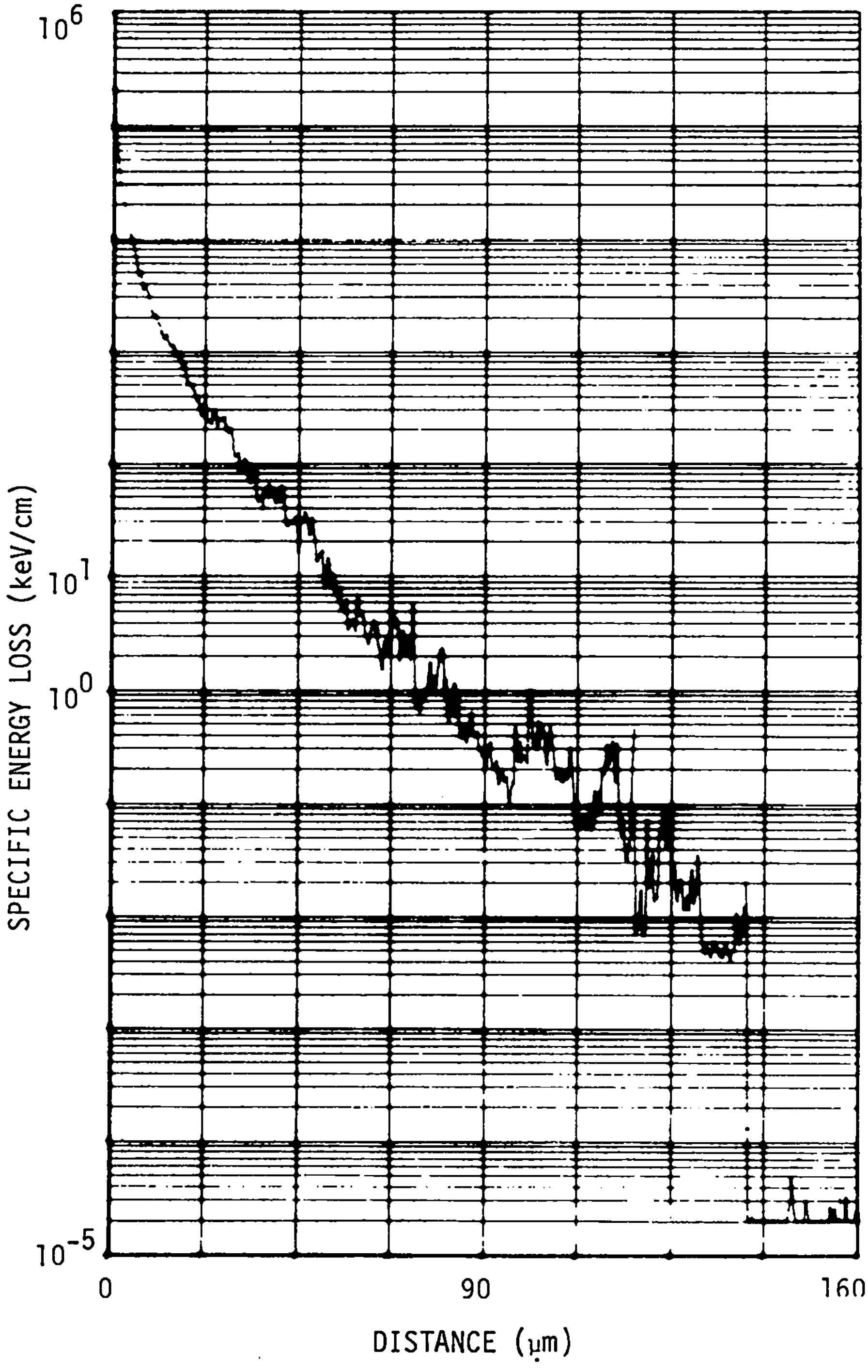

Fig. 5. Deposited specific energy vs depth for 60-keV electrons (Maxwellian distribution) in gold.

generated in the absorption processes. Since the ranges of electrons arising in the target interactions from lasers are even less than the ranges of heavy ions, the advantages of heavy ions for effective target coupling may be overstated.

Summary and Recommendations

Designs have been developed which show that an ion beam can drive an ICF target at the megajoule level. Depending on the degree of optimism or pessimism, one can design targets with projected gains of 1 to 100 at 1 MJ and gains of 100 to several hundred at 10 MJ. Principal uncertainties which underlie these designs are symmetry, ion ranges in hot material, and the fluid instability of imploding shells.

Present understanding of heavy-ion target physics is incomplete, but existing analyses suggest areas for significant future studies. For the near term, experimental studies are limited by the available accelerators. There are, however, several untested assumptions and computed results which could be verified using existing facilities. For example, the charge state of the incident ion varies as it slows down; the nature of this process materially affects the energy deposition. The computed charge states could be verified in beam foil spectroscopic measurements for ion beams available at the Bevalac heavy-ion accelerator. An important simplification in such near-term, low-intensity experiments is the use of cold target material, which relieves any questions concerning the target state.

An important next step in experimental target physics studies would be to have available a capability to perform target interaction experiments at conditions well above ordinary target temperatures, even if not at fusion target conditions. The validation of hot-material target physics assumptions would be an important outcome of such experiments. An accelerator providing at least 10 kJ per pulse would provide such a capability, possibly for considerably less investment than that represented by a HIDE. It is recommended, therefore, that serious consideration be given to the development of such an accelerator for continued assessment of heavy-ion fusion target concepts. It should be kept in mind that a target physics facility would offer unique opportunities for near-relativistic heavy-ion research.

VI. TECHNICAL ISSUES FOR APPLICATION OF HEAVY-ION FUSION TO COMMERCIAL POWER PRODUCTION

Introduction

Proponents of Heavy-Ion Fusion have expressed enthusiasm for this concept based on premises that: (1) the target interaction physics is "classical" and, therefore, better understood than for laser/plasma physics; (2) the applicable accelerator technology is well in hand and, therefore, a high-energy, high-current accelerator can be designed and built without new major technology development; and (3) the thick-fluid-wall reactor concept can be adapted for coupling with an accelerator system.

The first two premises are discussed in detail in other portions of this report. The third premise is discussed below with emphasis in two areas; the engineering problems of interfacing the reactor and accelerator system, and a comparison of HIF and laser-fusion systems requirements.

Engineering Problems of the Reactor/Accelerator Interface

The major engineering design consideration for an ICF reactor is the survival of surfaces that are subjected to the various forms of energy output from the microexplosion. Upon comparison of HIF target designs with laser-driven targets, the fractional yields and spectra of x-rays, ion debris, and neutrons are expected to be similar. Therefore, reactor designs to accommodate laser-driven targets should also be feasible for heavy-ion-driven targets. There are three general classes of reactor designs:

1) Solid wall with sacrificial liner (a small fraction of the liner is lost with each shot). A variation of this scheme is the deflection of ion debris away from a cylindrical surface using an axial magnetic field. These concepts impose no constraint on background pressure.

2) A gas-filled cavity at 10 torr or higher in which the x-ray and ion debris energies are absorbed and attenuated by creation of a blast wave.

3) Fluid-wall cavities in which the exposed surfaces are protected by a layer of lithium. Thin layers absorb the x-ray and ion energies, while thick layers also absorb most of the neutron energy. In these concepts, the target firing rate is limited by the capability to restore the initial cavity conditions, and the background pressure is determined by the vapor pressure of lithium at its initial temperature.

In general, the reactor dimensions of all three designs scale with the square root of yield. Solid-wall concept diameters are limited by ion debris and/or x-ray fluxes, with values of 10-20 m for a 150-MJ yield at a target firing rate of 10 Hz. Gas-filled cavity diameters are limited by wall impulse loading to values of 10-15 m for a 150-MJ yield. Thin fluid-wall cavity diameters are limited by damage from neutron fluence to values of 3-4 m for a 150-MJ yield at a target firing rate of 1 Hz. Thick fluid-wall cavity diameters are limited by wall impulse loading to values of 2-3 m for a 150-MJ yield.

In the considering the use of these concepts for HIF, the crucial technical constraint is the propagation of the beam from the final focusing magnet to the target. For example, at the current reference range of ion kinetic energies (5-10 GeV), the maximum propagation distance through background pressures $> 10^{-3}$ torr while maintaining the desired spot size appears to be less than 5 m. This constraint eliminates the gas-filled cavity as a feasible concept. The feasibility of the solid-wall concepts may be in doubt when the space-charge effects at vacuum conditions for long transport impose the use of a large number of beams. Thus, the fluid-wall concept emerges as the most likely contender for reactor design.

Fluid-Wall Reactor Design

The diameters of reactors based on fluid-wall concepts appear small enough for beam propagation, but the following additional problems must be considered:

For any fluid-wall concept, a significant fraction of deposited energy (essentially all the energy in the case of a thick-fluid-wall) appears as momentum rather than as energy supplied to vaporize lithium. This results in the possible formation of (submicron particle) mist, and imposes great uncertainty on the time required to restore initial cavity conditions. If repetition rates are limited to much less than 1 Hz, severe economic penalties may result; e.g., requiring either several cavities with beam-switching or high driver energies giving high yields to achieve reasonable power levels.

The close proximity of the final focusing magnet to the microexplosion will require innovative shielding design to prevent overheating and/or damage to insulation. The fast neutron flux which results from streaming through the transport tube is estimated to be 10^{13} n/cm-s at a distance of 5 m and an average power of 150 MW, and will obviously impose severe shielding requirements.

Comparison of HIF with Laser Fusion

Target Gain and Driver Efficiency - Target gain as a function of incident beam energy is fundamental in consideration of any ICF driver, and, over the past several years, target calculations have provided widely variant results. Over the past year, the estimates of target gain as a function of input beam energy have decreased by a factor of ~ 5 with an uncertainty by a factor of ~ 2. Such a wide variation (an order of magnitude) is very significant from a systems aspect and is attributed to the fact that the calculations are made with a complex code which has been normalized to results from 10.6- and 1.06-μm laser/target experiments at beam energies at 10 kJ or less. The uncertain- ties result from extrapolation to energies of 1 MJ or greater, and are not likely to be resolved until experimental results are available at driver energies greater than 100 kJ.

A clear advantage of heavy-ion accelerators is the potentially higher efficiency than that of lasers. It has been estimated from conceptual design studies that one might expect an efficiency of 10% for a CO_2 laser system and 5% for KrF, whereas the efficiencies of heavy-ion accelerators might be as high as 25% or more. This is important from a systems aspect because a higher target gain (defined as yield/driver output beam energy) will be required for lower driver efficiences to achieve the same engineering gain (defined as net power produced/power consumed in plant processes). The engineering gain may be expressed as:

$$Q_e = \eta_c \eta_d \, (G+1) - 1$$

where η_c = thermal to electric conversion efficiency
η_d = driver efficiency
G = target gain (yield/driver output beam energy)

Therefore, to a first approximation for high-gain targets, the engineering gain is directly proportional to the product $\eta_d G$, so that for the same Q_e, the gain required for the CO_2 laser is 1/2 that for KrF and the gain required for HIF is 1/5 that for KrF. Further, if one accepts the current gain scaling curve, i.e., $G \propto E_d^{0.5}$, where E_d is the driver output energy, and if one assumes that the gain coefficient is the same for heavy ions and KrF, then the heavy-ion driver energy would be 1/25 that of KrF to achieve the same Q_e. Such estimates are crude because the gain curves may not scale over such a large range in driver energy. More importantly, the Q_e chosen for any system will be determined by minimum power cost, not maximum or equivalent Q_e.

Driver and Other Systems Cost - It is necessary, in order to develop a basis for a systems choice, that the effect of driver cost on electric power production cost be considered.

The "accelerator community" has considered driver cost to be proportional to total beam energy to the exponent 0.4 for ecomonic analysis of HIF power production. According to this assumption, HIF accelerators have favorable cost scaling laws compared to lasers, for which detailed system concept studies indicate driver cost proportional to total energy to the exponent 0.8. Recently, however, target designers are requesting lower ion kinetic energies, and potential stability problems (particularly in storage rings) are dictating a decrease in the charge state. These new requirements may force accelerator cost scaling laws to be more consistent with lasers and other complex equipment in a power plant.

The existing economic analyses, therefore, are suspect, and their sensitivities to the scaling exponent have not been investigated. Before reasonable economic comparisons can be made between HIF conceptual designs and laser systems, conceptual design studies are needed to validate the scaling laws used and determine the sensitivities involved.

Conclusions and Recommendations

The only clear advantage of heavy-ion fusion over other ICF concepts is the potential for significantly higher effective driver efficiencies, including target coupling efficiencies. This can either reduce the target gain to achieve the same engineering gain or provide more "network" power if the gain characteristics are the same. However, a systems design and analysis using comparable capital cost data should be completed to verify this advantage.

The most crucial parameter for ICF economics is target gain as a function of input beam energy. At present the uncertainties are too great to make reasonable comparisons. However, if predictions continue to become more pessimistic with time, the commercial feasibility of any ICF concept will be in serious doubt.

The most challenging engineering problem may be the selection of a reactor concept and design of the final beam transport system consistent with limitations on beam propagation distance and isolation from the "hostile" reactor cavity environment.

It is therefore recommended that a systems study be conducted to include a conceptual design study of the complete accelerator system to determine scaling laws over the beam energy range of 1-10 MJ with parametric sensitivities of ion kinetic energy and charge state. This study should include a capital cost data base consistent with that developed for laser-fusion ICF systems. In addition, an engineering design study of selected reactor concepts should be carried out with emphasis on the problem of locating and protecting the final beam transport magnets from the cavity environment. This study will need to be closely coordinated with theoretical beam/target interaction and beam propagation studies.

VII. MILITARY APPLICATIONS

The weapons-laboratory applications of ICF all stem from the observation that drivers of interest to the military/civilian ICF program have the intrinsic capability to create, on a small scale, energy densities comparable to those found in a functioning nuclear weapon. This capability accounts for the expectation that at least one of these drivers--built big enough--will succeed in imploding and igniting a fusion microexplosion.

Nuclear weapons applications of ICF can be described in three categories:

1) Experimental physics data at high energy densities.
2) Implosion dynamics experiments and observations.
3) Weapons effects simulations.

Categories 1) and 2) involve no fusion, except perhaps where fusion neutrons can be "cooked off" as a useful diagnostic. The end product of work in these areas is knowledge rather than functioning hardware. Category 3) leads to a tangible product, but only upon successful solution of the problem central to ICF: implosion to ignition and burn. As one moves down the list from 1) to 3), the driver energy required escalates markedly. No existing machine even begins to approach the capability required for a single fusion microexplosion. The military goals of the Office of Inertial Fusion (OIF) program are reflected in a program of physics experiments aimed at acquiring data for weapons interests along with a fundamental understanding of implosion physics, and yielding, if successful, an effective economic system for weapons effects simulation.

Physics Experiments

The value of the ICF program to weapons research and development derives largely from the accessibility and high available repetition frequency of ICF experiments in comparison to full-scale nuclear tests. Given the proper drivers (discussed later in this section), physics experiments in category 1) should allow determination of equation-of-state and transport properties (viscosity, relaxation rates, emission coefficients) in previously inaccessible regimes of time, temperature, and density. Such data would serve to validate calculation models presently used in weapons (and ICF) design, and could conceivably point the way to new classes of weapons.

Implosion Experiments

Implosion dynamics experiments (category 2)) will emphasize direct observation of the effects of drive asymmetries, growth and control of instabilities, and verification of computer models. These experiments generally require more driver output than the simpler physics experiments, and present difficult diagnostic problems. Nevertheless, such experiments allow a direct attack on classic problems of weapons design. Under test ban conditions, experiments of this type could be the only escape from the computer available to the thermonuclear designer. If conditions of the ban were favorable, or if a civilian power goal continues to provide motivation, implosion physics experiments would assume great importance. Even with continued nuclear testing, the opportunities for systematic variation of parameters in an extended sequence of shots, and for definitive observation, make implosion experiments a valuable supplement to the main-line weapons development program.

Weapons Effects

Qualification of defense systems against a nuclear threat will continue to be needed should nuclear testing cease, and there is always interest in doing this in the least costly way possible even if testing remains available. Fusion yields of order 100 MJ would provide exposure fluences adequate to meet most of the DoD requirements now met by expensive underground nuclear tests. Such yields will obviously not be available until the ICF program passes the major hurdle of achieving ignition and burn.

Driver Considerations

A number of drivers with potential for military application of ICF are now in various stages of development. A subset of these which also show potential for civilian energy application are of interest in the OIF program: lasers, light-ion pulsed-power accelerators, and heavy-ion accelerators. Discussion here will therefore be confined to only these three, with emphasis on the role of heavy ions.

Assuming solution of several key problems, there appears to be little to choose technically between lasers, light ions, and heavy-ion drivers for the end-point applications of simulation and weapons effects source design. That is, with megajoule energy and $\sim$100 TW power outputs any of these drivers could fill the bill, so a selection would be based on other considerations such as cost. Differences become much more striking, however, at lower driver energies of more immediate interest to weapons physics experiments. To reach a given temperature in a target used in experiments under categories 1) and 2), the great depth of energy deposition for an ion driver, compared to that of a laser driver, is a major handicap. For certain flat target experiments, with target size chosen to minimize two-dimensional effects, simple estimates indicate a 1-kJ pulse would be satisfactory for a laser driver, while U^+ ions with kinetic energies of interest would require pulse energies of at least 100 kJ. While heavy-ion accelerators may offer advantages for civilian power application, and could also be effective drivers for weapons effects simulation, they appear clearly inferior to lasers for the nearer-term application as a research tool.

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