LA-UR-86-2045

CONF-8606131--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

RECEIVED BY OSTI JUL 07 1986

TITLE: DIRECTIONS FOR REACTOR TARGET DESIGN BASED ON THE U.S. HEAVY ION FUSION SYSTEMS ASSESSMENT

LA-UR--86-2045

DE86 012415

AUTHOR(S):
D. C. Wilson
D. Dudziak
G. Magelssen
D. Zuckerman
D. Dreimeyer

SUBMITTED TO: Second International Topical Symposium on ICF Research by High-Power Beams, Nagaoka, Japan
June 16-18, 1986

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

OSW

Directions for Reactor Target Design Based on the U. S. Heavy Ion Fusion Systems Assessment*

D. C. Wilson, D. Dudziak, and G. Magelssen
Los Alamos National Laboratory
Los Alamos, New Mexico, U.S.A.
and
D. Zuckerman and D. Dreimeyer
McDonnell Douglas Astronautics Co., P.O. Box 516
St. Louis, Missouri, U.S.A.

Abstract

The Heavy-Ion Fusion Systems Assessment project, with the participation from Los Alamos National Laboratory, Lawrence Berkeley Laboratory (LBL), and Lawrence Livermore National Laboratories (LLNL), the U.S. Departmart of Energy (U.S.DOE), the University of Wisconsin, the Electric Power Research Institute (EPRI), and McDonnell Douglas Astronautics Co., is nearing completion of a two-year effort. The system model it produced for a fusion power facility is used to set directions for future target design work. We studied areas of major uncertainty in target design using the cost of electricity as our figure of merit. Net electric power from the plant was fixed at 1000 MW to eliminate large effects due to economies of scale. The system is relatively insensitive to target gain. Factors of three changes in gain cause only 8 to 12% changes in electricity cost. An increase in the peak power needed to drive targets poses only a small cost risk, but requires many more beamlets be transported to the target. A shortening of the required ion range causes both cost and beamlet difficulties. A factor of 4 decrease in the required range at a fixed driver energy increases electricity cost by 44% and raises the number of beamlets to 240. Finally, the heavy ion fusion system can accomodate large increases in target costs. To address the major uncertainties, target design should concentrate on the understanding requirements for ion range and peak driver power.

---

*This work was supported by U.S.DOE and EPRI

Introduction

Although we attempt to calculate the performance of inertial fusion reactor targets, we are a long way from experimentally verifying their performance. In fact we expect that poorly known effects such as drive asymmetry, instability growth, mix, and fabrication imperfections can substantially degrade target performance. This is why the "best estimate" gain curves of Lindl and Mark[1] differ from the "ideal" by as much as a factor of 10. On the other hand gain curves are derived for specific target designs. Advanced concepts do exist for which curves have not been calculated. When we are able to study targets experimentally, measured gains will differ substantially from those predicted now. We can expect the gain of these targets to increase with driver energy, but little more can be said with confidence.

In addition to target gain, the actual beam pulse length, spot size, and range required by the target are uncertain. Target designs and performance span a multidimensional space including these and other variables. In this paper we will use the results of the U.S. Heavy Ion Fusion Systems Assessment (HIFSA) to quantify the importance of each of these factors to the cost of electricity. This can then be used to guide target designs toward the most important regions of the multidimensional space.

Systems Assessment

In September 1984, the U.S. began a two-year assessment of heavy ion fusion concepts based on an induction linac driver. Los Alamos coordinated the effort of numerous participants including LBL, LLNL, McDonnell Douglas Astronautics Co., Sandia National Laboratories, Stanford Linear Accelerator Center, and the University of Wisconsin. The assessment was funded by the U.S. Department of Energy through the Offices of Inertial Fusion, High Energy and Nuclear Physics, and Program Analysis, and by the Electric Power Research Institute. It was to emphasize design innovations and identify parameter ranges that offer promise for reductions in size, cost and complexity. It considered only induction linac drivers and only electric power applications.

As a tool to perform the assessment, McDonnell Douglas created a computerized systems model incorporating target physics models from LLNL and Los Alamos, linac and final transport models from LBL, reactor cavities from Los Alamos and LLNL, and many other subsystems.

The accelerator model[2] is based upon more than 500 discrete accelerator designs generated with LBL's LIACEP code. These calculations determined the accelerator efficiency, cost, and length over the following variable ranges: repetition rate (5 to 20 Hz), ion mass (130-210 amu), ion energy (5-20 GeV), driver energy (1-10 MJ), emittance (15-30 μrad-m), number of beams (4-16), and ion charge state (+1 and +3). The system model uses a polynominal fit to these calculations. Late in the study, LBL realized that using multiply charged ions was feasible and substantially reduced accelerator cost and length, and its efficiency. As a consequence fewer runs were made with +3 charge state, but these results were extrapolated over the variable range using fits to the +1 accelerator calculations. The final transport model[3] includes bunching to the required target pulse length with a momentum spread of 0.1% at the final focusing lens. Emittance, aberations, and beamlet perveance define the final focus angle and limit the current per beamlet. We assume 80% charge neutralization.

We chose to explore four developed reactor cavity concepts:[4] a magnetically protected wall, a liquid wall (based on HYLIFE), a granular wall (based on CASCADE), and a wetted wall.[5] These reactors differed in many ways including operating temperature, wall life, acceptable irradiation schemes, and maximum number of beams. The most important difference for this paper is the maximum repetition rate. For the liquid wall, 2 Hz, for the granular and wetted walls, 10 Hz, and for the magnetically protected wall, 20 Hz. Cavity clearing calculations require these rather low rates and suggest operating at relatively high pressures near 0.01 torr. While we have attempted to cost all cavities comparably, we view the granular walls as the most optimistic and the liquid wall as the most conservative. For this paper we will focus on the wetted wall exclusively, seeking to understand the effects of target design rather than comparing reactor concepts.

The system model includes a number of target types and illumination geometries. In normal operation, the code requires a specification of gain as a function of driver energy, gamma (spot radius$^{3/2}$ x range), and pulse length. For the single- and double-shell targets we have the Lindl-Mark[1] curves. These targets can use either single- or double-sided illumination. The range multiplied target uses the single-shell gain curves and pulse lengths, but the allowable ion range is increased by a factor of 2. The advanced target is simply the single-shell target with gain multiplied by three at each driver energy. One design for such a target might incorporate polarized DT.[6] For a symmetrically illuminated target we use Magelssen's gain relations.[7] Together these targets cover most of the heavy ion target concepts.

McDonnell Douglas, LLNL, and Los Alamos all contributed to the balance of plant modeling.[8] We have determined the system cost and the cost of electricity in two ways: one consistent with magnetic confinement fusion systems like STARFIRE, the other consistent with the Nuclear Energy Data Base. At this time, both approaches give identical costs of electricity. The target cost modeling[9] is the most sophisticated and complete such model in existence. It includes capital costs for the target manufacturing facility, which increase with the number of targets to the 0.65 power, representing economies of scale. It also includes facility operations and maintenance costs, which increase with the number of targets. Costs for target materials and waste disposal that scale with beam energy mass and number of targets will soon be added to the system model. Although target costs are very uncertain, this model allows us to explore the consequences of much more expensive targets.

To determine global minima in the cost of electricity the system code generated a data base file of roughly 20,000 variations of target type, gamma, repetition rate, ion charge, number of accelerated beams, driver energy, and net electric power. This data base could then be searched for minimum electricity cost under various conditions and could look at system variations that gave a cost of electricity within 5% of the minimum. These results are used to address the system sensitivity to various changes.

Preliminary Results

We focused our analysis on a power plant size, which U.S. utilities currently desire, producing 1000 MW of electricity. With this constraint we found a standard system configuration that produced nearly minimum costs of electricity for each of the four different reactor cavities. This system uses +3 ions with a mass of 130 amu in a 16-beam accelerator to irradiate single-shell targets from two sides. For the magnetically protected wall the minimum cost of electricity is 70 mills/kwh, for the liquid wall, 69 mills/kwh, for the wetted wall 59 mills/kwh, and for the granular wall, 54 mills/kwh. When we combine the granular wall reactor with advanced target and single-sided illumination, we achieve our most optimistic result of 49 mills/kwh. For this paper, we will focus on the more conservative wetted wall results. We believe our conclusions extend to the other cavities with minor modifications.

Because the driver and other plant costs scale weakly with electric power output, the cost of electricity decreases rapidly with electric power production. For the standard system at 500 MWe the cost is 96 mills/kwh; at 1000 MWe it is 59 mills/kwh, and at 1500 MWe it is 45 mills/kwh. To compare HIFSA results with other systems, we need to account for differences net power as well as costing procedures. If we cost the HIBALL-II[10] system on a comparable basis we derive an electricity cost of 46 mills/kwh, but at a net electric power of 3784 MW. Scaling these results to 1000 MWe, we obtain 95 mills/kwh. Our discussion here will consider the net electric power fixed at 1000 MWe.

The greatest uncertainty in gain relations is the gain itself. How sensitive is the HIF system to gain? One approach to answering this is to consider different gain curves. If we multiply the single shell gain by 3 at each driver energy (the Advanced Target curves) then the cost of electricity is reduced from 58.8 to 54.6 mills/kwh. The decrease in repetition rate from 5 to 3 Hz and driver energy from 5.8 to 5.2 MJ have resulted in roughly comparable cost decreases through out the system.

Figure 1 shows another way to look at the variation of cost of electricity with gain. To completely specify a system at each point within this gain and energy space, we need gamma and the pulse length on target. We have assumed that gamma varies as driver energy$^{5/6}$ and is normalized to 0.02 at 5 MJ (near the optimum standard system value). Using this scaling of gamma we derive the target gain curve shown in Fig. 1. The target pulse length should scale with the target radius and therefore driver energy$^{1/3}$. This we normalized to 6.25 ns at 1 MJ by fitting the Lindl-Mark power curves. By holding the net electric power fixed at 1000 MW the repetition rate is constrained to lie along curves like the dashed lines in Fig. 1. Because the wetted wall cavity is limited to at most 10 Hz in our model, and because system costs increase substantially when a second cavity is added, cost contours are only shown at 10 Hz and below. A lower limit on driver repetition rate is 1 to 2 Hz. Here we use an extrapolation from the 5 Hz LIACEP calculations. Acceptable systems lie between the two repetition rate curves. Contour lines of constant electricity cost are labeled by the percentage difference from 59 mills/kwh. The lowest electricity cost along any gain curve is where that curve is just tangent to the lowest cost contour. In Fig. 1, the 0% cost difference contour is just tangent to the gain curve at 5.8 MJ, as in the standard system. If the gain curve were shifted upward by a factor of three (the advanced target), electricity cost would be about 8% lower. Similarly if the gain were reduced by a factor of 3, then electricity would cost about 12% more. Figure 1 graphically quantifies the relative insensitivity of electricity cost to gain. If targets can only achieve low gain at high driver energies, say gain 40 at 10 MJ, electricity cost would only be increased by about 20%. This is an advantage unique to high efficiency drivers such as a heavy ion accelerator.

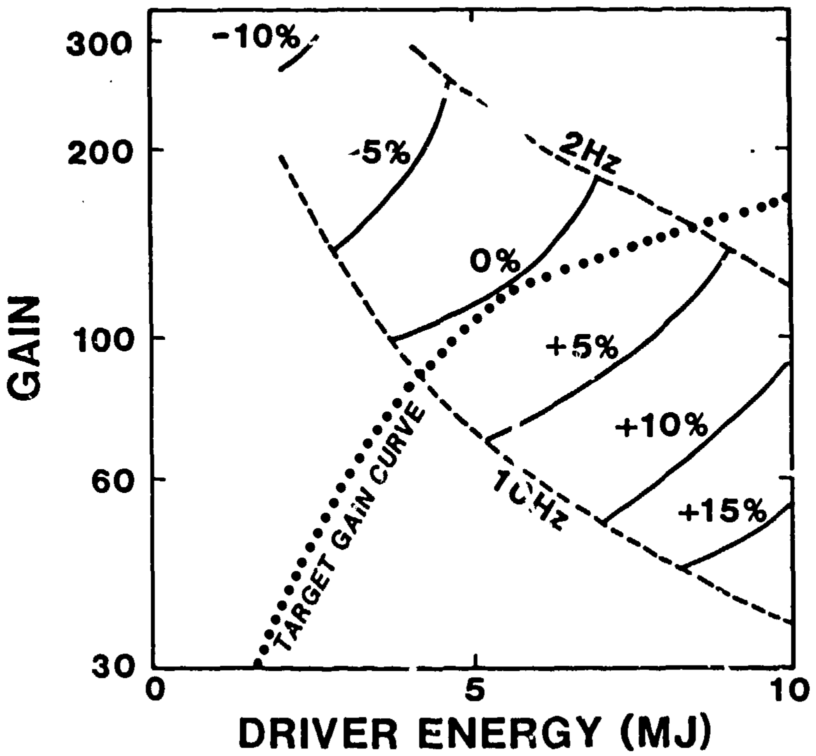

Figure 1. Electricity cost using single-shell targets with two-sided illumination, nominal gamma and pulse length scaling, and 1000 MW electric power. The minimum electricity cost along the gain curve is 59 mills/kwh (labeled 0%).

After gain, the greatest uncertainty in target performance is the peak power required to drive a capsule. Double-shell capsules are thought to require less power than single shells, perhaps a factor of 2 lower.[1] However, even the peak power required by single-shell targets is very uncertain. Replacing the single shell gain relations with those for the double-shell targets gives a slight increase in electricity cost, 59.8 vs 58.8 mils/kwh. This effect is caused by both an increased pulse length and a change in the gain curves. Although double-shell targets have the potential for higher gains than single shells, the somewhat arbitrary degradations introduced in the Lindl-Mark "best estimate" curves place double shell gains below the "best estimate" gains for single-shell targets. The double-shell target causes a decrease in the number of beams required in final transport from 28 to 16, which leads to lower final transport costs. The lower gain requires more driver energy and a higher cost accelerator.

Since increasing power on target is a difficult task for heavy ion drivers, a major risk for an HIF system is that higher powers are required for all targets. We have attempted to model this case in Fig. 2 by normalizing the scaling of pulse length to 1.55 ns at 1 MJ, about 1/4 of nominal. The shape of the cost contours is similar to Fig. 1, but the minimum cost along the gain curve is now 68.6 mills/kwh, up 17% from nominal. Achieving increased target gain at lower driver energies could only recover part of this increase. The number of beamlets in final transport has now increased from 28 to 120. Although the increase in final transport costs is relatively small, this will require either splitting the beams after exiting the accelerator and before final bunching, or carrying all 120 beams through the linac. The challenge posed by a decrease in required pulse length appears more technical than costly.

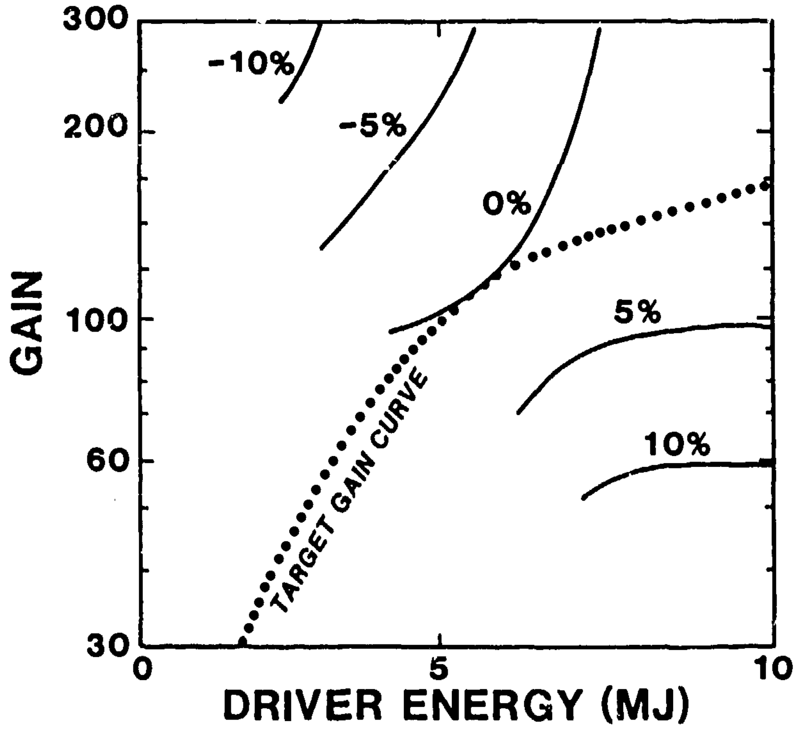

Figure 2. Electricity cost using single-shell targets with two-sided illumination, nominal gamma, and 1000 MW electric power, but 1/4 the pulse length. The minimum electricity cost along the gain curve is 69 mills/kwh (labeled 0%)

A third uncertainty in the gain relations is the required ion range. To understand the importance of increasing the ion range, we have introduced the range multiplied target. Its gain curve is simply that of the single-shell target with the range requirement reduced by a factor of 2. Using this gain curve the system optimizes at a cost of 55 mills/kwh. The optimization resulted in an increased gain at slightly lower driver energy with the same actual ion range.

Figure 3 shows the energy and gain space cost curves under a different scenario. We assume that the gamma required at any point is 1/4 of the nominal scaled value. We also assume that the target size is unchanged so that $0.1 < r(cm)/E(MJ)^{1/3} < 0.2$. In the optimal case the cost of electricity is 84.9 mills/kwh, 44% above nominal. The ion range has decreased from 0.23 g/cm^2 to 0.05 g/cm^2 with a corresponding decrease in ion energy from 8 to 3 GeV and little change in the driver energy. The total driver cost has increased from \$940 to \$1690 million. The number of beamlets on target has increased from 28 to 330. Under this less favorable scenario both the cost of electricity and the number of final beams have increased substantially.

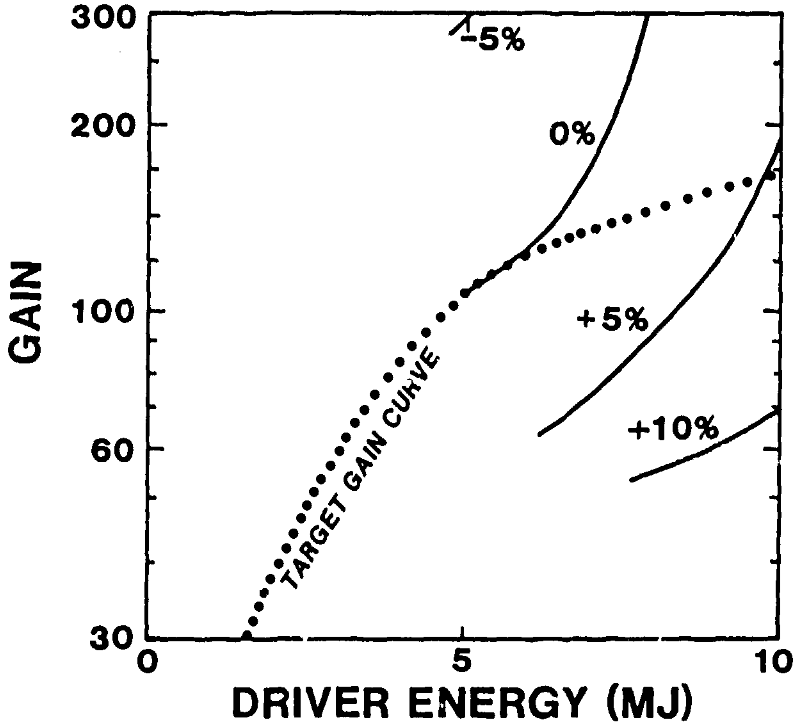

Figure 3. Electricity cost using single-shell targets with two-sided illumination, nominal pulse length, and 1000 MW electric power, but 1/4 the gamma. The minimum electricty cost along the gain curve is 85 mills/kwh (labeled 0%).

The one cost factor in this system model with perhaps the most uncertainty is the cost of targets. In Fig. 4, we have multiplied the target cost by a factor of 10. Since we do not yet know how to manufacture a single pellet, such a large variation is not unreasonable. Here the cost contours are substantially different from Figs. 1-3. Since the target factory capital and operating costs increase with the number of pellets produced, the system is driven to higher gain and lower repetition rate. In the standard system target costs were 8.1% of the total and the repetition rate was 5 Hz. The system is now driven to the limits of driver energy and gain with a resulting repetition rate of 1.4 Hz and electricty cost of 83.3 mills/kwh, a 42% increase. Perhaps the only technical difficulty with such a system would be the low repetition rate and correspondingly low driver efficiency. A direction to reduce costs is to increase the repetition rate and net electric power while still using a single reactor cavitity.

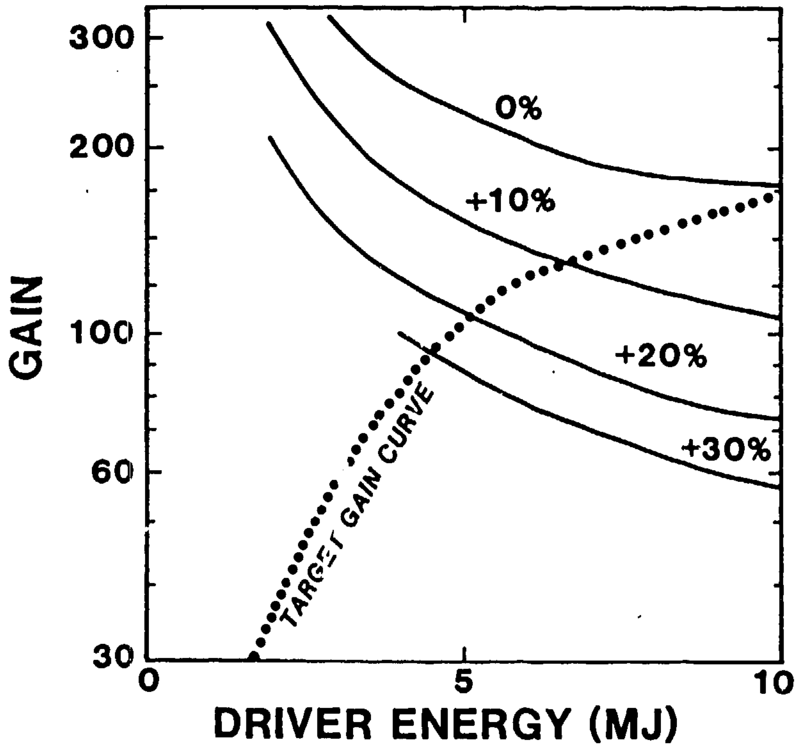

Figure 4. Electricity cost using single-shell targets with two-sided illumination, nominal pulse length, nominal gamma, and 1000 MW electric power, but ten times the target costs. The minimum electricity cost along the gain curve is 83 mills/kwh (labeled 0%).

Conclusions

A heavy ion fusion system for electric power production is relatively insensitive to target gain. A factor of 3 increase in gain at a fixed driver energy leads to only an 8% decrease in the cost of electricity. A factor of 3 decrease leads to only a 12% increase in cost. Because a heavy ion driver is efficient and its cost scales weakly with energy delivered to a target, commercial power production is feasible even if targets can produce only low gains at high driver energies.

An increase in the peak power needed to drive targets poses only a small cost risk to heavy ion fusion. A factor of 4 increase leads to only a 17% increase in the cost of electricity. However, the number of beamlets transported to the target also increases by a factor of 4. This poses the technical problem of either transporting yet higher currents per beamlet, increasing the beams in the accelerator, or splitting accelerator beams with little growth in emittance.

A shortening of the required ion range causes both cost and beamlet difficulties. A factor of 4 decrease in the range required at a fixed driver energy increases electricity cost by 44% and raises the number of beamlets to 330.

The heavy ion fusion system can accomodate large increases in target costs. If target costs are increased by a factor 10, then the system is driven to the limits of low repetition rate and high driver energy, in this case 1.4 Hz and 10 MJ. Electricity cost is raised 44%, but this may be counteracted by operating at higher net electric power.

To address the major uncertainties target design effort should concentrate on understanding the required ion ranges and peak driver power. While gain is important, it is not as crucial for a heavy ion fusion power plant.

References

1. J. D. Lindl and J.W-K Mark, "Recent Estimates on the Energy Gain of Cryogenic Single Shell Ion Beam Targets," 1984 INS International Symposium on Heavy Ion Accelerators and their Applications to Inertial Fusion, January 23-27, 1984, Institute for Nuclear Study, Tokyo, 629.
2. J. Hovingh, E. P. Lee, A. Faltens, and V. O. Brady, "A Comparison of the Design and Costs of Induction Linac Drivers for Inertial Fusion Using Ions of Differing Mass," presented at the 7th Topical Meeting on the Technology of Fusion Energy, June 15-19, 1986, Reno, Nevada, to be published in a special issue of Fusion Technology.
3. E. P. Lee, "Accelerator and Final Focus Model for an Induction Linac Based HIF System Study," 1986 International Symposium on Heavy Ion Fusion, Washington, D. C., May 27-29, 1986.
4. J. H. Pendergrass and W. R. Meier, "Reactor Designs for Heavy Ion Fusion", presented at the 7th Topical Meeting ...
5. J. H. Pendergrass, T. G. Frank, and I. O. Bohachevsky, "Modified Wetted Wall Inertial Fusion Reactor Concept," Proceedings of the 4th Topical Meeting on the Technology of Controlled Nuclear Fusion, King of Prussia, Pennsylvania, October 14-17, 1980. U.S.DOE report CONF-80101, 2, p. 1131, July 1981.
6. J.W-K. Mark and Y. L. Pan, "Factors of Two Reductions of Beam Energy and Peak Power Requirements in Targets for Heavy Ion Fusion," Bull. Amer. Phys. Soc., October 1985, 20, 1633.
7. G. R. Magelssen, "Gain Scaling Relations for Heavy Ion Targets," presented at the 7th Topical Meeting ...
8. D. S. Zuckerman, D. E. Dreimeyer and L. M. Wagner, "Systems Performance and Cost Model for Heavy Ion Fusion," presented at the 7th Topical Meeting ...
9. J. H. Pendergrass, D. B. Harris, D. J. Dudziak, and K. W. Billman, "Heavy Ion Fusion Target Cost Model," presented at the 7th Topical Meeting ...
10. B. Badger et al. "HIBALL-II An Improved Conceptual Heavy Ion Beam Driven Fusion Reactor Study," report KfK-3840, December 1984.