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INERTIAL-FUSION REACTORS

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DESIGN CONSIDERATIONS FOR DIRECT-ILLUMINATION-DRIVEN
INERTIAL-FUSION REACTORS*

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ABSTRACT

This study parametrically examines the implications on inertial-fusion-reactor design of the use of direct-drive pellets as an alternative to the radiation-driven targets. We have examined the impacts of direct illumination on mirror damage constraints, reactor neutronic performance, and system energetics and cost. The capital costs for low f/number, direct-illumination-driven inertial-fusion power plants are required to be significantly less than those for the radiation-driven or high f/number direct-illumination-driven power plants to produce electricity at the same cost.

INTRODUCTION

Inertial fusion reactions for power generation require high energy drivers to compress and ignite the fusion fuel pellet. Two techniques for producing uniform irradiation of the fuel considered here: radiation-driven, and direct-illumination-driven targets.

The radiation driven targets use a high-Z radiation case and convert the driver beam energy to x rays. This radiation case provides a hohlraum-like region, which results in relatively uniform irradiation of the pellet with as few as two, high f/number driver beams. The direct illumination driven pellets absorb the driver energy directly in the expanding plasma from the fuel capsule. Direct drive pellets require a

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large number of globally distributed driver beams to produce sufficiently uniform coupling of the driver energy to the spherical ablator shell of the pellet. The final optics for the driver beam can be either 'defocused' high f /number optics or low f /number optics. Velocity asymmetry must be kept to less than about 4%.¹

Some recent conceptual designs for inertial fusion power reactors are suitable for the radiation driven pellets. These designs usually feature high f /number driver beams entering the reactor cavity from essentially two sides.²⁻⁴ In this study we parametrically examine the implications of the use of direct drive pellets as an alternative to radiation-driven targets on inertial fusion reactor design.

We consider three types of issues here: 1) mirror damage constraints, 2) reactor neutronic performance, and 3) system energetics and cost. But first, we need to discuss pellet illumination and performance.

PELLET ILLUMINATION

The direct illumination pellets may use either a large number of either high f /number "unfocused" laser beams or low f /number beams. Most of the effort on pellet illumination studies has been focused on the use of low f /number final optics.

Both Howard and Trenholme have investigated the uniformity of illumination of spherical laser fusion pellets using low f /number optics. Howard found the 20-beam illumination system to be slightly better than 12-beam illumination, with 8 beams running a poor third.⁵

Trenholme examined the uniformity of illumination for the LLNL Shiva laser⁶ and the Nova laser.^{7,8} For Shiva, Trenholme investigated 12-, 20-, and 32-beam illumination systems. For Nova, Trenholme investigated 8-, 10-, and 12-beam geometries. The 10-beam system was selected for Nova as it is more cost-effective than the 12-beam system.⁸ Trenholme folded in the absorption of the 1- μ m photons as a function of the incident angle to obtain an estimate of 0.5 as the total effectiveness (product of absorbed energy fraction and fill factor) of the 10 beam, 5+5 geometry system with 100° beam cone angle and $f/4$ optics.⁸

PELLET PERFORMANCE

Asymmetries in target illumination are one of the causes of implosion instabilities which degrade directly-driven pellet performance. These asymmetries are due to the finite number of driver beams producing spatial non-uniformities in the ablation pressure over the pellet surface. Bodner has proposed using infrared photons as the driver output to smooth the non-uniformities by thermal diffusion.¹ However, infrared photons do not couple their energy well to the target due to photon scattering processes. In addition, the production of hot electrons by the Raman scattering of the infrared photons preheat the pellet fuel, resulting in a degradation of the pellet performance.

Radiation driven targets may have higher gains than directly illuminated targets for driver energies greater than several megajoules. These higher gains are due to the increased "implosion efficiency" defined as the overall energy efficiency with which the driver beam couples to the target. However, researchers at KMS, NRL, and the University of Rochester are attempting to develop direct illumination reactor targets with both the required implosion symmetry and as high an implosion efficiency as that of the radiation-driven targets.⁹

Additional considerations to pellet gain are the cost of producing the pellets and the survival of the pellets during injection into the reactor chamber.¹⁰ The direct-driven targets may be simpler and cheaper to fabricate than the radiation-driven targets.

OPTICAL DESIGN CONSTRAINTS

A design strategy for the final optics is that the final focusing mirrors should operate at the laser damage limits to minimize the size (and cost) of the optics. They should be protected by 10 torr-m of xenon, which will not only thermalize the debris energy, but will also attenuate the x-ray energy. Following this strategy, the lifetime of the final focusing optics will be determined by neutron damage. This lifetime will increase as the distance squared from the fusion microexplosion. Since the change-out problems will be independent of the

f/number of the optics, fast optics with short lifetimes will result in a lower plant availability than operating with slow optics. This lower plant availability results in an increased loss of revenues, which will require, for a given capital cost of the plant, higher prices for the plant product.

Another strategy is to minimize the cost of the final optics by considering both the cost of the optics and the loss of revenues resulting from their frequent replacement caused by neutron damage. The optics will operate at less than the laser damage limit which will increase their cost because of the increase in size. They will then be further removed from the microexplosion which reduces the neutron flux and increases the lifetime of the optics. The implementation of this strategy for power reactors will require data on neutron damage to optical materials.

REACTOR ISSUES

The direct-illumination-driven, inertial fusion reactors will have different design constraints than the radiation-driven, inertial fusion reactors. The direct-drive reactors will require more driver beam penetrations, and these beams may have lower f/number final focusing optics. The primary issues will be neutronic, but other issues such as cooling and maintaining the final optics and shielding behind the penetrations through the reactor vessel, as well as containment considerations will also be important design constraints.

Neutronics

Three-dimensional neutronic calculations were performed on a reactor blanket with illumination ports located at the center of a duodecahedron and an icosahedron. The first wall of the blanket is located 5 m from the 14.1 MeV neutron source. The 0.7-m-thick blanket has a 10% volume fraction of 2.25 Cr-1 Mo ferritic steel with the remaining 90% volume fraction filled with a working fluid. A 0.3-m-thick graphite reflector is located immediately behind the blanket region, with a 50-mm-thick structure of 2.25 Cr-1 Mo steel vacuum vessel encapsulating the reactor.

A comparison was made of how two working fluids affect the blanket energy multiplication and the tritium breeding ratio. These working fluids are either natural lithium, or a natural lithium-lead compound with a nominal chemical composition of $\text{Li}_{17}\text{Pb}_{83}$.

The results of the TARTNP¹¹ runs using the LLNL Evaluated Nuclear Data Library (ENDL) for the 12 beam, duodecahedron arrangement and for the 20 beam, icosahedron arrangement are shown in Fig. 1. Also shown on each of the figures is the f/number of the beam ports.

The results for a given working fluid are virtually the same for the two geometries, for the same beam port solid angle fraction. The results for these three-dimensional geometries are also virtually the same for all solid angle fractions between zero and 10%, just as in the two-dimensional geometry considered by Meier.¹²

The solid angle fraction occupied by the beam ports affects both the tritium breeding ratio (tritons per source neutron) and the blanket energy gain (energy per unit energy of the 14.1 MeV source neutrons). For a given number of driver beams, decreasing the f/number of the final focusing system to accommodate faster optics will result in an increase in the beam solid angle fraction which results in a decreased tritium breeding ratio and a decrease in the total blanket energy gain.

A minimum allowable tritium breeding ratio of 1.05 is selected as the controlling design criteria. The maximum solid angle fraction of the beam ports for a lithium-lead blanket with a tritium breeding ratio greater than 1.05 is 2%, which translates into a minimum f/number of the beam port of 6.1 for the 12 beam, duodecahedral arrangement, and 7.9 for the 20 beam icosahedral arrangement. The blanket energy multiplication factor will be greater than 1.25. The maximum solid angle of the beam ports for a natural lithium working fluid with the same tritium breeding ratio constraint is 14%, with a minimum f/number of the beam ports of 2.3 for the duodecahedron and 3.0 for the icosahedron. The blanket neutron energy gain factor is 0.95 for the lithium blanket.

The tritium breeding ratio and the blanket neutron energy gain factor decrease faster than the simple ratio of $(1-\Omega')$ where Ω' is the solid angle fraction taken by the beam ports. This result, shown by Meier and in Figs. 1 and 2, is dependent on the blanket material. The

1a. duodecahedron

1b. icosahedron

Fig. 1 Tritium breeding ratios and blanket neutron energy multiplication factors and f-number for two illumination geometries as a function of total beam port solid angle for Li and Li₁₇Pb₈₃ blanket.

spectrum of the neutrons that escape from the beam ports with the lithium blanket is harder than that escape from the lead-lithium blanket. For the case of the blankets with a 10% solid angle beam port fraction, the neutron energy leakage through the ports is about the same for both blankets, but the neutron number leakage through the ports of the lithium blanket is about 2.3 times that of the lithium blanket.

There are several methods that can be used to increase the tritium breeding ratio and neutron energy gain factor for a given beam port solid angle fraction. For the lithium blanket there are three options: increase the ^6Li concentration;^{14,15} use a neutron multiplier such as beryllium or lead with a natural lithium blanket,¹⁶ or a combination ^6Li enrichment with a neutron multiplier. For the lithium lead blanket, the tritium breeding ratio and the blanket neutron energy multiplication factor can be increased by enriching the natural lithium with ^6Li .

The tritium breeding ratio and the blanket neutron energy multiplication factor can be maintained greater than unity even with fast final focusing optics by extending the breeding blanket along the periphery of the beam port cones and behind the final focusing optics. This blanket extension will not only breed tritium, but also will be the neutron shield for the beam ports. However, these blanket extensions would require complex and costly plumbing systems, with allowances for the periodic removal of the final optics.

Other Reactor Issues

Shielding will be required around the beam ports and behind the final focusing optics to prevent direct streaming of the 14-MeV neutrons into the containment building. These shields and the final focusing optics must be cooled to remove the neutron and x-ray energies deposited. For reasonable lifetimes of the final focusing optics the energy flux on the optics must be low, which results in low energy densities with the concurrent low grade heat. This heat will probably be dumped to the environment rather than utilized in the reactor system thermal cycle. The plumbing that provides cooling for the final focusing mirrors must be designed for remote maintenance.

The mirrors must be mounted on stable platforms to reduce jitter. Since these mirrors will be spotted globally 10 to 20 m outboard from the reactor vessel, a class I containment building would either be very large, or must have a large number of penetrations for the 10-30 driver beams. These penetrations must allow isolation between the reactor containment and the laser building to minimize the potential of tritium leakage from the containment building. Thus, a large number of final mirrors will add complexity to the reactor analogous to the complexity of large number of magnets intrinsic to a tokamak magnetically confined fusion reactor.

SYSTEM ISSUES

The primary system issues for any power plant include both the system energetics and a revenue-to-cost analysis.

The electric power ratio, defined as the ratio of the net electric power to the grid to the gross electric power produced, as a function of the solid angle for the beam entry ports for various fusion gains (ηQ , where η is the driver efficiency and Q is the target gain) is shown for the $\text{Li}_{17}\text{Pb}_{83}$ blanket in Fig. 2a and for a natural lithium blanket in Fig. 2b. Also shown in each figure is the tritium breeding ratio and the f /number of the beam entry ports for a duodecahedral and an icosahedral driver beam arrangement. For this analysis, 68% of the fusion energy was in neutron energy, the thermal to electric conversion efficiency was 35% and 3% of the electric power was used for plant auxiliaries. The blanket energy gains were obtained from Fig. 1.

An increase of the solid angle fraction of the driver beam entry ports will require an increase in the fusion energy gain ηQ to maintain the same revenue per unit of capital cost. From another perspective, increasing the solid angle fraction without increasing the fusion energy gain will require a higher price of electricity to produce the same ratio of revenue to capital cost.

Example for Fast Final Optics

Consider a direct illumination inertial fusion reactor system using an optical arrangement with 24 beams with $f/3$ final focusing optics. The

2a. $\text{Li}_{17}\text{Pb}_{83}$ blanket

2b. Lithium blanket

Fig. 2 The ratio of net to gross electric power as a function of beam port solid angle for various fusion gain (ηQ) for two blanket compositions. This ratio is a measure of the revenues to cost of the plant. Also shown is the tritium breeding ratio and the f-number for two illumination geometries as a function of solid angle.

solid angle fraction of the beam ports is 16%. From Fig. 2a, the tritium breeding ratio is less than 60% for a $\text{Li}_{17}\text{Pb}_{83}$ blanket. Thus, the use of a lead-lithium blanket can be eliminated for this system. From Fig. 2b a lithium blanket will give a tritium breeding ratio of 1.0, which is marginal if tritium losses in the recovery of the tritium from the blanket and cavity and in the pellet fabrication process are considered.

Assume a 3-MJ driver for the system with a pellet gain Q of 200. We need at least 10 m of 1 torr of xenon to protect the final optics from the pellet debris and x rays. The xenon gas region is located in the beam port external to the 6-m-radius reactor cavity. Thus, the final focusing mirrors are located a minimum distance of 16 m from the microexplosion. Based on the laser damage considerations, the f/number for the 24 beams located 16 m from the microexplosion must be less than $f/6$ using a 3-MJ driver, which is satisfied by the $f/3$ optics assumed for which the laser fluence is 7 kJ/m^2 per shot.¹⁶

This reactor system will use a lithium blanket, and the 24 $f/3$ final focusing mirrors (5-m diameter) must be located at least 16 m from the microexplosion.

Now let us compare the performance of this system with a radiation-driven inertial fusion reactor with two arrays of $f/50$ final focusing mirrors. For a 5% efficient laser, the fusion gain nQ will be 10. From Fig. 2b, the direct-illumination system will have about 90% of the revenue per unit of capital cost of the radiation-driven system. Thus, for the same cost of electricity, the capital cost of a \$1.5B plant must be reduced 10%, or \$150M. Therefore, the direct-drive laser, optics and pellet production systems must be a total of \$150M cheaper than that of a radiation-driven system to produce the same ratio of revenue to capital cost. Alternatively, to produce the same ratio of revenue to capital cost at the same price of electricity for the same laser efficiency, the direct-illumination system will require a 30% higher pellet gain for the same laser energy as the radiation-driven system!

Example for Slow final Optics

For a direct-driven system featuring "defocused" high f/number optics, for the same nQ the ratio of revenue to capital cost will be

the same as for the radiation-driven power plant. Bechtel¹⁷ performed a cost analysis of an 8-beam, high f/number system, and found that the direct capital cost of the reactor containment building and the optical system is $2.25 \times$ the cost of a 2 beam system. This cost differential represents \$15M. This minimal cost differential may be partially or totally offset by the higher capital costs of the target factory for producing radiation-driven targets vis a vis the cost for the factory producing direct-driven pellets. Thus, for the same nQ the direct-driven power plant will be virtually equal on an economic basis as the radiation-driven power plant for the same pellet gain.

CONCLUSIONS

The use of directly-illuminated pellets is an alternative to the radiation-driven pellets for inertial fusion power plants. The direct-drive reactor system appear to have several undesirable constraints compared to the reactor system for the two beam, high f/number radiation driven microexplosions. The design constraints caused by the globally distributed multitude of beam ports include: Reduced blanket material options, and increased size (and cost) of Class I containment. However, the pellet production costs may be lower than for the radiation-driven pellets. The economic penalties from the energy lost through these beam ports include: A reduced plant availability factor due to more frequent final focusing mirror changeouts required because of damage from the neutron energy leaking through the ports, and reduced revenue from the sale of electricity for a given plant capital cost.

The direct-illumination-driven inertial fusion power plant using fast final focusing optics may not compete economically with the radiation-driven inertial fusion power plant for a given fusion gain. The use of high f/number final focusing optics for direct illumination will minimize the economic penalty relative to the fast final optics, but, with the exception of the reduced blanket material options, is still subject to the design constraints described above. For a given driver energy above several MJ, the radiation-driven pellets are likely to have a higher gain than the direct-driven pellets. This will further enhance

the economics of radiation-driven fusion reactors for a given cost of electricity. However, a complete design of an innovative direct-driven reactor including optics and pellet factory should be performed and compared with a complete design of a radiation-driven reactor and its associated pellet factory and optics. The designs must include the appropriate pellet design, damage threshold of optics to photons, x rays, and neutrons, as well as the complete design of the laser system. Then the cost of electricity from the two types of target drives can be quantified and more rigorously compared.

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