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Power Plant and Fusion Chamber Considerations for Fast Ignition

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Abstract

1. Introduction

A large number of inertial fusion energy (IFE) chamber concepts have been proposed and analyzed to various levels of detail [1, 2]. A smaller number of detailed power plant design studies (i.e., studies considering self-consistent integration of targets, drivers and chambers) have also been completed for both direct-drive and indirect-drive, central ignition (CI) targets [3-5]. There have not been any comparable studies of fusion chambers or integrated power plants for fast-ignition (FI) based IFE. Some specific aspects (advantages and issues) have been previously describe [6, 7], but not to the level of detail of the large integrated design studies. In this paper, we review current understanding of chamber design and power plant features for fast-ignition.

We approach this topic by asking what chamber and power plant issues and features will be different for fast ignition compared to central ignition. In this article, we consider first wall and final optics design issues for various chamber concepts with direct and indirect drive FI targets, while target manufacture and injection issues are considered in another paper in this special issue [8]. If it is found that the ignitor beams can efficiently penetrate the plasma that is blown off the fuel capsule surface during the compression phase, the FI targets may look much like CI targets. In this case the fusion chamber and final optics issues are likely to be very similar to those for CI targets, except for the final optics of the ignitor beams. It is more likely that the efficiency of transferring ignitor beam energy through the blow-off plasma to the ignition spot fuel will be so low that whatever advantage fast ignition has in reducing required compression driver energy will be more than offset by the size and, therefore, cost of the ignitor lasers themselves. Therefore, it has been proposed to use a cone of high-Z material [9] to shield the ignitor beam line-of-sight from the blow-off plasma and possibly help focus the short pulse ignitor beams onto the dense fuel. Figure 1 illustrates what these cone focus targets might look like for laser direct-drive, laser indirect-drive and heavy ion indirect-drive concepts. The Tabak article in this special issue describes the operation and performance of these targets [10]. The cones must be relatively heavy and thick to avoid breaking up during the implosion of the fuel. In the direct-drive case, the cone must also be long enough that ablated material from the fuel capsule does not go around the end and into the ignitor beam line of sight. It has been suggested that the cone length may have to be up to four times the initial radius of the fuel capsule [7]. For hohlraum targets, the cones need not be as long because the hohlraum wall itself retards the expanding plasma.

[Figure 1]

The presence of the massive high-Z cone in close proximity to the high density fuel will affect the energy partition of the burning capsule output and its x-ray and debris spectra. It can also affect the aerodynamics of the target during injection. Finally, if the capsule fails to ignite, the consequences of the dud may be different for cone targets than for central ignition targets. All these potential differences will be examined in this article.

In Section 2, we discuss the power plant benefits of FI cone-focus targets with emphasis on the economic advantages of high target gain at low driver energy. Section 3 shows how the energy partition and spectra of cone focus targets compares with central ignition targets. Section 4 covers possible chamber concepts that are compatible with indirect-drive fast ignition. Section 5 reviews two special issues for FI power plants: Section 5.1 describes the survival of final optics, especially for the extremely intense ignitor beams, while Section 5.2 discusses the consequences of duds, which may occur more frequently for FI targets. Section 6 lists recommended near-term future work for FI power plant issues discussed in this article, and Section 7 gives our conclusions.

2. Potential Power Plant Benefits of FI versus Central Ignition

Without the need to form a central hot spot and with a reduced fuel density requirement, compression driver beams for fast ignition could be much less energetic (and therefore cost much less). Figure 2 shows target gain for direct-drive CI with a 0.5 μm laser and the comparable FI gain curve with a 0.5 μm compression laser. The CI gain curve is from work by Perkins [11], and the FI curve is from Fig. 17 of the Tabak article in this issue [9]. Note that for FI, the laser energy is the sum of the compression laser and ignitor laser energies. This figure shows that with FI the gain curve is shifted dramatically to the left and up, i.e., much higher gains at much lower driver energies.

[Fig. 2]

High gain at low driver energy reduces the recirculating power fraction and the importance of high driver efficiency. The recirculating power for the driver (P_D) is:

$$P_D = P_E / (\eta G M \varepsilon) , \tag{1}$$

where P_E is the total electric power produced in the plant, η is the driver efficiency, G is the target gain, M is the ratio of thermal energy to fusion energy, and ε is the thermal to electric energy conversion efficiency. Once the recirculating power fraction is below about 10%, reducing the recirculating power further has a much smaller marginal effect on the cost of electricity (COE), and the increased gain can be used to relax the driver efficiency requirement.

We have developed a simple systems model for COE to illustrate the effects of the improved gain with FI. We assume $500/J for the laser and used the chamber and plant cost scaling developed for the Sombrero power plant study [12]. For the FI case, the cost per joule for the ignitor laser is assumed to be a multiple of the compression laser cost per joule, ranging from equal cost to 10 times more expensive. We have also assumed that the ignitor energy is a fixed 25% of the total laser energy, consistent with Tabak [9] for in-flight aspect ratios less than about 100.

Figure 3 shows the normalized COE as a function of laser energy for the two cases. It is seen that the minimum COE for the FI concept is lower and to the left (i.e., at a lower driver energy) of the minimum of the CI target. To the right of the minima the increasing driver costs causes the COE to increase, while to the left of the minima (where the plant net output power is maintained by shooting smaller, lower gain targets at a faster rate) the increased cost of high recirculating power for the laser causes the rise in COE. The FI COE has a minimum at about 1.2 MJ total laser energy (i.e., 900 kJ compression and 300 kJ ignition) and is about 21% lower than the CI COE, which minimizes at about 2.8 MJ. Fig. 3 show the most optimistic case for FI since the ignitor laser unit cost ($/J) is taken to be equal to the compression laser unit cost.

[Fig. 3]

Since there will be a limit to how high a repetition rate is achievable (due to chamber clearing or target injection constraints), Fig. 3 also shows the rep-rate required for a 1000 MW_e plant. In this example, the minima both occur at about 10-11 Hz, which is likely acceptable.

Figure 4 shows the sensitivity of the COE results to the relative cost of the ignitor laser. If we hold the total the energy fixed at 1.2 MJ in order the keep the rep-rate about 11 Hz, the COE increases to 90% and 103% of the CI COE for ignitor laser unit costs of 5 and 10 times the compression laser unit cost. The optimum COE points are at slightly lower laser energies, but corresponding rep-rates of 19 and 24 Hz (not shown) may be difficult to obtain depending on the chamber type.

[Fig. 4]

While we generally compare power plants for a fixed net power, other comparisons are possible and instructive. Figure 5 shows the total net power that can be generated as a function of the total capital investment. Total capital investment may be an important criterion for future power plant investors seeking to generate and sell power into an open market (as opposed to the regulated utilities seeking to meek a particular power demand). As indicated, for a given investment, the FI plant can generate significantly more power. For example, if limited to $4B, the FI plant can generate 1240 MWe compared to only 760 MWe for the CI plant, i.e., 63% more net power. One can also compare investments at a fixed net power, e.g., the CI plant cost about $1B (33%) more than the FI plant at a fixed 750 MWe. Note that these results assume that the ignitor laser has the same $/J cost as the compression laser; higher ignitor laser costs would diminish the FI advantage.

[Fig. 5]

A FI power plant will also be more competitive at smaller plant size than CI. Figure 6 shows the normalized COE as a function of net power production. The FI plant could be as small as 625 MWe for the same COE as the CI plant at 1000 MWe (assuming no cost penalty for the ignitor laser). At 5x higher unit cost for the ignitor laser (not shown), the plant size could still be reduced to 800 MWe.

[Fig. 6]

Finally, Fig. 7 compares the optimal driver energy as a function of net power. The total FI driver energy (compression plus ignition) is more than a factor of two smaller over the range shown. In additional to the cost savings reflected in the previous figures, this gives and indication of the scale of the laser facility.

[Fig. 7]

The simple economic model used here shows a rather dramatic potential advantage for the FI concept compared to power plants using conventional central ignition targets. In fact the advantage is probably larger due to some other benefits not accounted for in the present economic model. Because a lower overall fuel density is needed (100-300 g/cm^2 vs. 500-600 g/cm^2) and because the main driver does not have to form a central uniform ignition hot spot, the drive symmetry, beam uniformity and target surface roughness requirements are greatly relaxed. These advantages should translate into reduced driver and target factory cost not accounted for in the above economic model. Furthermore, high gain with relaxed symmetry raises the possibilities of one-sided illumination of indirectly driven targets and of using thick-liquid-wall chambers like HYLIFE-II [3,13]. Use of such chamber concepts would result in longer-life structures, again reducing the cost of a FI power plant relative to a conventional IFE plant.

3. Energy Partition and Spectra

The presence of high-Z cone materials close to the burning DT can alter the energy partition and the x-ray and debris spectra of the targets. It can also alter the isotropy of the target output. The output partition, spectra and angular distribution of the output are needed to calculate the effect of the target on the first wall and final optics of the chamber concepts. John Perkins has done calculations of target output and spectra for CI targets for the ARIES-IFE study [14]. Similar calculations of cone-focus FI targets are needed.

Table 1 shows the energy partition for CI direct-drive and indirect-drive targets. As can be seen, the presence of the high Z hohlraum greatly increases the x-ray output and greatly decreases the output of fast ions and debris. Comparing a hohlraum target to a direct-drive target, the amount of energy in the ions (burn ions plus debris ions) is decreased by about a factor of five. Specific ions are absorbed more readily, however. The alpha particles, for example, are reduced by about three orders of magnitude. The high Z material absorbs much of the debris and fast ions, and when hot, is a very good radiator of x rays. Figure 8 shows the x-ray spectra of direct and indirect drive central ignition targets as calculated by Perkins [14].

[Table 1]

[Fig. 8]

The presence of the cone will also affects the x-ray, ion and debris spectra, but the effect in the cone focused targets is smaller because the cone subtends only a portion of the solid angle. Although detailed calculations have not been completed, we can make a rough estimate of the effect of the cone. A 35° (half-angle) cone subtends about 9% of solid angle surrounding the compressed core where fusion burn occurs. Therefore, for a direct-drive FI target, about 9% of the ion energy could be converted to x-rays. Using the fractions from Table 1, we'd expect an additional ~3% (i.e., 0.09×0.28) of the yield in x-rays for a total x-ray fraction of ~5% instead of 2%. The importance of this shift depends on the first wall concept.

4. Chamber Concepts and Issues for Indirect-Drive FI Targets

In this paper, we focus on indirect-drive FI. Researchers at Osaka are beginning to explore the chamber issues for direct-drive FI [15].

Because of the need for illumination from a large number of angles, power plants proposed for laser driven CI targets (whether direct or indirect drive) have frequently used dry-wall chambers like the Sombrero concept shown in Fig. 9. Most studies find this a workable plant, but it requires a very large containment building to accommodate the final optics from many angles.

[Fig. 9]

Moir [13] has pointed out the benefits of using thick-liquid-wall (TLW) chamber concepts like HYLIFE-II for heavy ion driven CI targets. In the cases he examined, ion beams came from both ends. Figure 10 shows an updated version of the HYLIFE-II chamber concept coupled with a heavy ion driver [16]. The ion beams are focused onto the target from opposite ends, each within a fairly tight cluster.

[Fig. 10]

Use of the TLW concept would reduce the size and cost of the containment building compared to the Sombrero concept. Figure 11 compares the sizes of the Sombrero and HYLIFE-II chambers to the NIF chamber and to a common fission reactor core. Sombrero is clearly the largest, and when the final optics are placed as in Fig. 9, the building must be very large (~ 90 m diameter).

[Fig. 11]

The thick blanket of flowing Li_2BeF_4 molten salt (flibe) absorbs all the x-ray and debris energy and most of the neutron energy. The neutron flux that reaches the chamber structures is significantly reduced and has a softer, less damaging spectrum. The wall lifetime, even with near-term ferritic or stainless steels, will be much longer, possibly for the life of the power plant. The TLW concept greatly reduces or eliminates the requirement to periodically replace the first structural wall, thereby increasing availability and reducing O&M costs. Finally, the TLW concept eliminated the need for a fusion neutron materials development facility, because the lifetime of the steel wall could be determined by tests in existing neutron facilities. This would reduce the time and cost of the development path. Thus, the ability to use the TLW concept offers many advantages to heavy ion fusion using indirect-drive CI targets.

The story for heavy-ion FI targets like the one shown in Figure 1c is not changed greatly. These targets use heavy ion beams for compression and short pulse lasers for ignition. The compression phase does not have to be as symmetric because no central hot spot need be formed. Therefore it may be possible that all the compression beams could come from one side allowing access from the opposite direction for the ignitor beams. The issues for this concept are whether the one-sided compression symmetry is adequate (detailed 2D calculations have not been done) and whether the background flibe vapor or droplets will disturb the intense ignitor beams.

These same considerations suggest that the cone-focus laser indirect-drive target of Fig. 1b may also allow use of the TLW concept. The fact that symmetry requirements can be relaxed for the compression beams may mean that the laser illumination can come from one end and from a smaller number of angles. While this has not yet been calculated, if the maximum cone angle for the illumination beams is small enough, then TLW chamber concepts can once again be considered for laser indirect drive. Even if grazing incidence metal mirrors were used for the final optics of the compression beams the surrounding building will be much smaller that that required for the Sombrero concept.

Determining whether the single-sided laser target of Fig. 1c or the single-sided heavy ion target can give sufficient gain at low drive energy and determining the minimum cone angles for illumination should be a high priority of fast ignition target designers. Because cone targets seem to give more than enough gain at low drive energy, some gain can be forfeited for the advantages of using the HYLIFE II chamber. As discussed in Section 3, the output partition and spectra for indirect drive FI targets will not be significantly different from those of central ignition targets. Thus HYLIFE II would be suitable for all indirect drive fast ignition targets. Furthermore the presence of the cone does not significantly alter the aerodynamics and, therefore, the injection issues should be the same as for CI indirect-drive targets.

The ignitor beams must, however, penetrate whatever background vapor fills the fusion chamber. For the thick liquid wall chamber, this will be residual vapor from the molten salt that is vaporized on each shot. At an operating temperature of ~600 C, the vapor pressure of the Li_2BeF_4 molten salt is $\sim 2\times10^{-6}$ atm and is dominated by BeF_2. If this material was completely ionized, the electron density would be $\sim 3\times10^{14}/cm^3$. Thus, even if the flibe only returns to within a couple orders of magnitude of its equilibrium vapor pressure between shots, the chamber electron density will be many orders of magnitude below the critical density for the ignitor laser ($\sim 10^{21}/cm^3$). For direct drive laser chambers, a 10-20 mtorr background gas (typically Xe) is used to reduce the x-ray load on the chamber first wall. This gives an atom density of $<10^{15}/cm^3$ and a potential electron density an order of magnitude higher (depending on ionization level), which is also many orders of magnitude below the laser critical density. Although detailed propagation calculations have not been done for the extremely short and intense ignitor beams (~10^{19}–10^{20} W/cm^2 near focus), it is expected that beam instabilities such as Stimulated Brillion and Simulated Raman scattering will not be a problem at these low background densities [17].

5. Other Fast Ignition Power Plant Issues

5.1 Final Optics

Chirped Pulse Amplification (CPA) lasers use diffraction gratings to recompress the beams to extremely high power (>10^{15} W). Optical elements after the gratings in the final optics package will be quite vulnerable to damage from such high power beams. The number of final optics required will depend upon size, fluence damage limit, and beam coupling efficiency, as seen in Fig. 12.

[Fig. 12]

If the number of ignitor beams is too large because of their optical damage limits, they might not fit in any reasonable cone-focus geometry. Additionally, the final optics will be subject to damage from the x-rays, neutrons and debris from the target explosions. It should be noted particularly that in a cone focused FI target, the high-Z cone material will tend to jet toward the FI ignitor beam final optics. If the diameter of diffractive optics is limited, they may not be able to be placed far enough away from the target to be protected from the target emissions. Development of large diameter diffractive optical components that are “tough” is a development need for FI ignitor beams.

It is not known how severe these problems with final optics will be and whether they will be concept limiting. A thorough analysis of all the possible damaging effects and options for FI ignitor beam final optics is badly needed. Only after such an analysis can it be determined if a self-consistent final optics package can be designed.

One promising development for FI ignitor beam final optics is the development of thin diffractive optics as focusing elements. Figure 13a shows an 80 cm diameter, 1-mm-thick fused silica Fresnel lens developed for the Eyeglass project at LLNL [18]. This lens has tabs along several radii to allow folding for transport into space. However, the fabrication technique (2-mask lithographic process with HF etching bath) could also result in a monolithic lens of the same size. Figure 13b shows and even larger Fresnel lens consisting of an array of such individual lenses. They can be accurately aligned to act like a single lens. If such an array of about 5 m diameter could be constructed and it were near diffraction limit, it might be located 15 m or more from chamber center and still have a small enough spot (~50 μm diameter) to ignite the fast ignition target. This would ease the final optic issue for fast ignition. New work on focusing the ignitor beam on a convex foil within the cone to produce ions, which then propagate to the compressed core, would allow larger spot sizes for the ignitor beams (~300 μm diameter) [19]. This would allow larger standoff for given size final optics making them easier to protect.

[Fig. 13 a&b]

5.2 Impact of Non-Exploding Targets (duds)

Mima has suggested that the dud rate for cone focus targets may be larger than for central ignition targets [20]. The compression may be much more turbulent if the illumination symmetry is relaxed. Since the ignitor beams are of very short duration, there may be an increased probability that the ignitor beams will hit a lower density spot in the target. This could, therefore, result in a larger dud rate for FI targets than for CI targets.

The economic model for laser driven plants was altered to illuminate the consequences of a higher dud rate (see Fig. 15). The FI Gain curves were multiplied by 0.6 to account for a dud rate of up to 40%. After re-optimizing, it was found that the overall economic penalty was small (FI at 85% instead of 79% of CI COE) even though the laser energy had to be increased by 33% from 1.2 to 1.6 MJ. This curve assumes ignitor laser unit cost is equal to the compression laser.

[Fig. 14]

A larger concern with cone targets is the damage from debris and shrapnel for a dud target. For a hohlraum target shrapnel and debris from a cone target will be about the same as for a central ignition hohlraum target. The concerns are greater, however, for direct-drive, cone-focus targets. Imagine the capsule in Fig. 1a vaporized but without producing fusion yield. The high-Z mass is all on one side of the compressed gas of the fuel capsule. If the target does not ignite, the cone itself will not be vaporized except at the very tip. Thus the rest of the cone will be accelerated by the ball of high pressure gas and will likely break up. Pieces may fly directly toward the final optics of the ignitor beams. Calculations of the size and direction of the shrapnel will be very important.

6. Recommendations for Future, Near-Term Work

Successful development of any IFE power plant will require many scientific and technological developments. Most of these fundamental developments are the same for fast ignition as they are for central ignition targets. Driver developers will have to show acceptable end-to-end performance and efficiency at reasonable cost. Target ignition and gain at reasonable driver size and acceptably high ηG (driver efficiency times target gain), typically ~10, will have to be demonstrated. The technologies necessary for target manufacture, injection and tracking must be demonstrated. High repetition rate operation and survivability must be demonstrated for fusion chamber systems.

This paper has discussed some of the benefits and unique issues associated with the use of fast ignition targets. Listed here are some key calculations needed for more detailed evaluation of the chamber and final optics issues presented by cone-focused FI targets.

Target Calculations:

1. Target implosion, ignition and burn. Detailed 2-D calculations of cone-focus direct-drive (laser) and indirect-drive (laser and ion drivers) to determine
    a. the minimum compression driver and ignitor laser size, illumination cone angles and beam balance necessary for single-sided illumination by the compression driver and opposite-end illumination by the ignitor laser,
    b. the minimum cone density, thickness and length,
    c. the dud probability.
2. Target output. Detailed 2-D long-time target output calculations starting with the compressed fuel cores and the condition of the cone and hohlraum (if used) material from the above ignition and burn calculations.
3. Dud output. Detailed 2-D long time target output calculations for unignited targets (duds). In particular, for the cone-focus the calculations should determine whether the cone and hohlraum (if used) is completely vaporized and, if not, what the size, energy and angular distribution of the particles will be.

Target Chamber Design Calculations and Experiments:

1. Threat to first wall and optics. The propagation of target outputs through chamber background gas and interaction with the first wall and final optics should be calculated to determine if current designs must be modified to accommodate FI targets (for both full yield targets and duds).
2. Debris propagation. Experiments that simulate the acceleration of the high-Z cone (and hohlraum if used) from a dud target to determine the expected angular distribution and whether any final optics protection from this debris is needed.

Ignitor Beam Propagation:

1. Calculations and experiments to estimate the propagation of the ignitor beams through chamber background gases.

7. Conclusions

Fast ignition has many potential advantages for IFE power plants but also raises new concerns and requires special developments. For indirect-drive, cone focused targets, the use of thick liquid wall chamber with its many advantage should be possible if 1) one-sided compression can be used and 2) if the cone angle for the ignitor beams is compatible with the liquid jet configuration. For both direct and indirect drive FI, propagation of the ignitor beams through residual chamber background must be demonstrated. Protection of the final optic of the FI laser is an added issue that must be addressed. The current FI program is focused on understanding the fundamental physics of beam/matter interactions and energy delivery to compressed core. We recommend some level of ongoing work on driver/chamber/target interface issues. Such integration studies can provide valuable input to the target physics and experimental programs and will help assure that the implosion/ignition concepts being investigated have the potential to lead to viable IFE systems.

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List of Figure Captions

Fig. 1. Three types of cone focus targets are shown in (a) Laser direct drive, (b) Laser indirect drive, and (c) Heavy ion beam indirect drive.

Fig. 2. Target gains are much higher at low drive energies for FI targets (solid) compared to direct-drive CI targets (dashed). ($\lambda = 0.5\ \mu$m)

Fig. 3. Normalized COE in (solid lines, left scale) and pulse rep-rate in Hz (dashed lines, right scale) for a 1000 MW_e power plant vs. driver energy for FI (red, x's) and CI (blue).

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Fig. 12. Number of ignitor beams required vs. final optic dimensions for 75 kJ ignitor energy coupled to compressed fuel core. Solid line = 25% coupling efficiency and laser damage limit of 4 J/cm^2; dashed = factor of two lower coupling efficiency (12.5%) or factor of two lower laser damage limit (2 J/cm^2); dash-dot line = factor of two higher coupling efficiency (50%) or factor of two higher laser damage limit (8 J/cm^2).

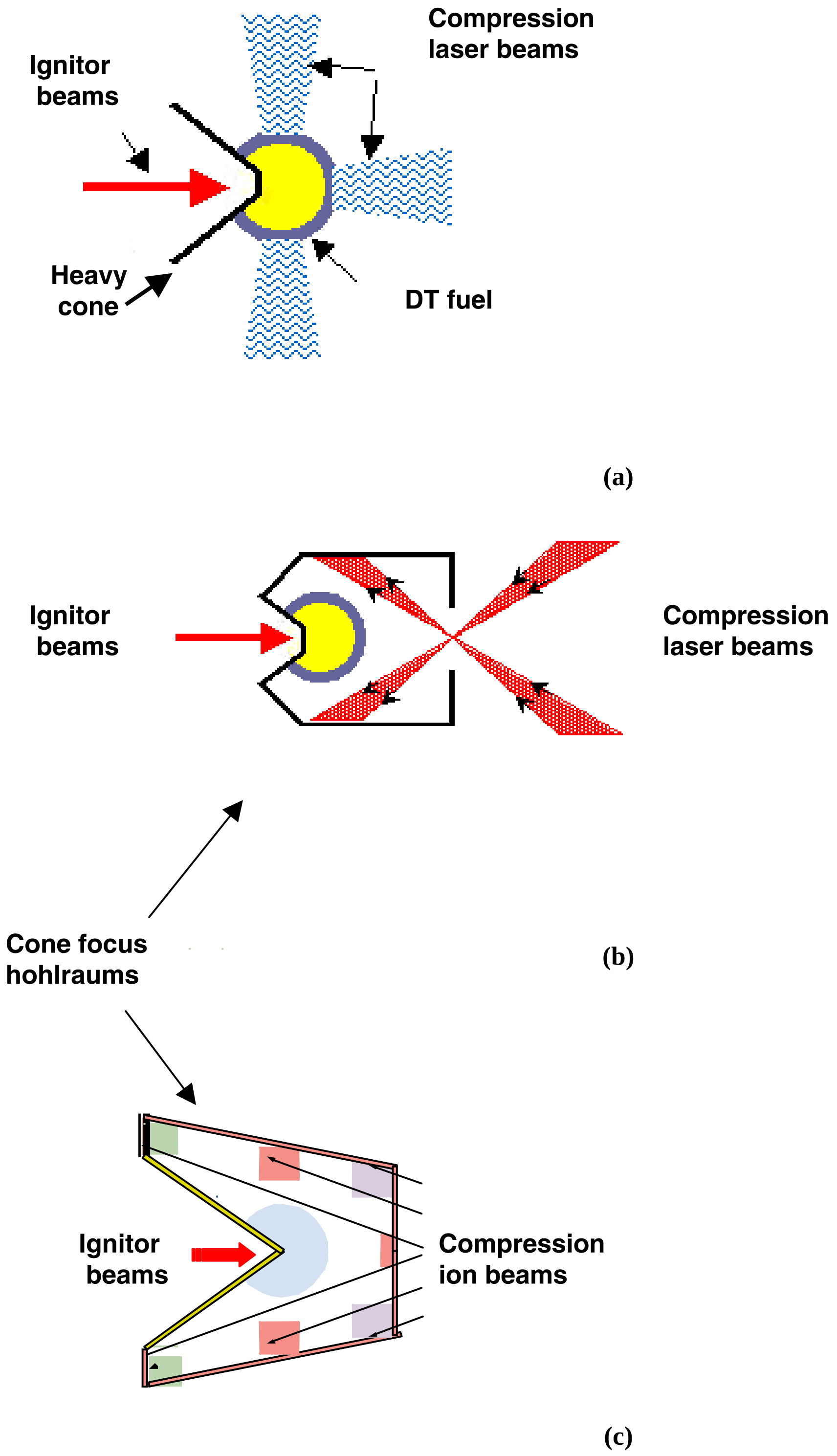
Fig. 13. (a) An 80 cm diameter, 1 mm thick Fresnel lens was fabricated in the Eyeglass project t LLNL. (b) An even larger Fresnel lens array was later fabricated.

Fig. 14. COE for fast ignition compared to central ignition assuming a 40% dud rate for FI targets.

Table 1. Energy partition of inertial fusion targets. Numbers are output energy in MJ for the capsule yield cited in bottom row. Numbers in parentheses are the percentage of the yield for that form of output.

Target type	CI DD[a] Target (MJ)	CI HI ID[a] Target (MJ)
X-rays	6.1 (2%)	115 (25%)
Neutrons	279 (70%)	316 (69%)
Gammas	0.017 (0.004%)	0.36 (0.1%)
Burn product fast ions	52.2 (13%)	8.43 (2%)
Debris ions kinetic energy	60.0 (15%)	18.1 (4%)
Total Yield	397	458

[a] CIDD = Central Ignition Direct Drive, CIHIID = Central Ignition Heavy Ion Indirect Drive, calculations done by John Perkins



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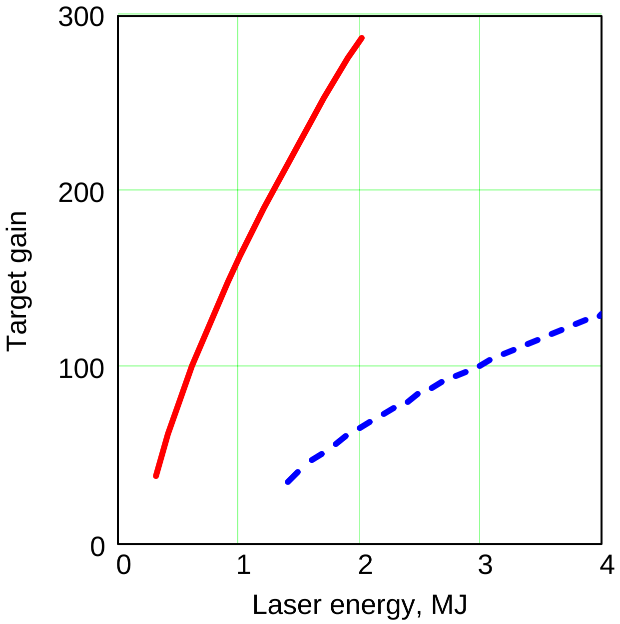

Fig. 2. Target gains are much higher at low drive energies for FI targets (solid) compared to direct-drive CI targets (dashed). (λ = 0.5 μm)

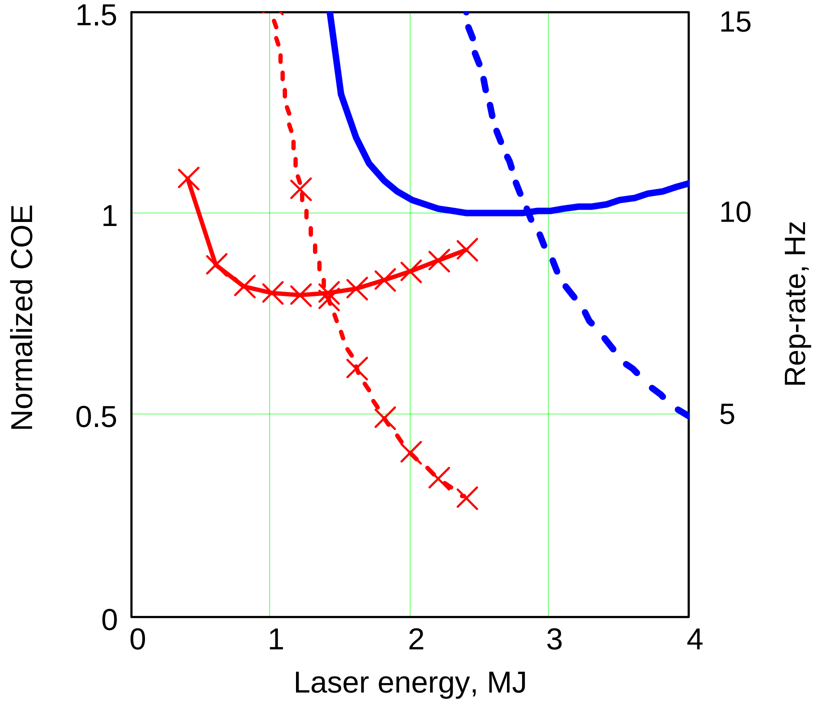

Fig. 3. Normalized COE in (solid lines, left scale) and pulse rep-rate in Hz (dashed lines, right scale) for a 1000 MW_e power plant vs. driver energy for FI (red, x's) and CI (blue).

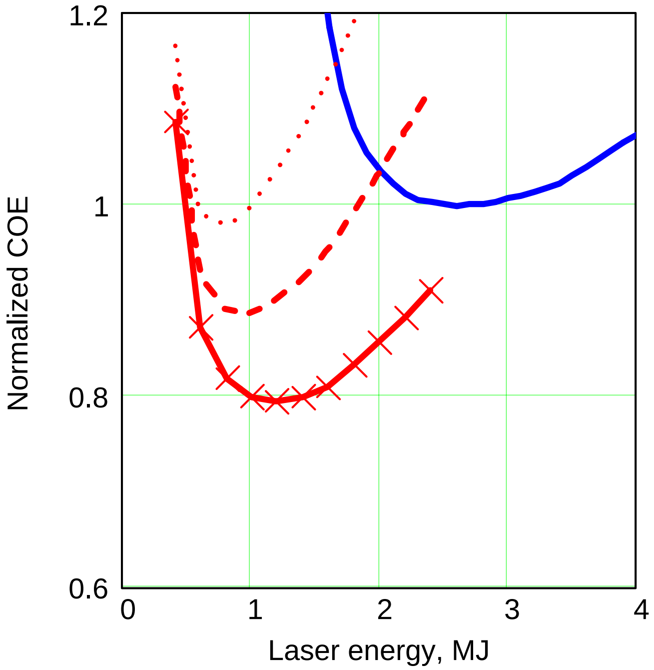

Fig. 4. Normalized COE versus driver energy for CI (solid blue), and FI target and ignitor laser unit cost ($/J) one (solid, x's), five (dashed), and ten (dotted) times the compression laser unit cost.

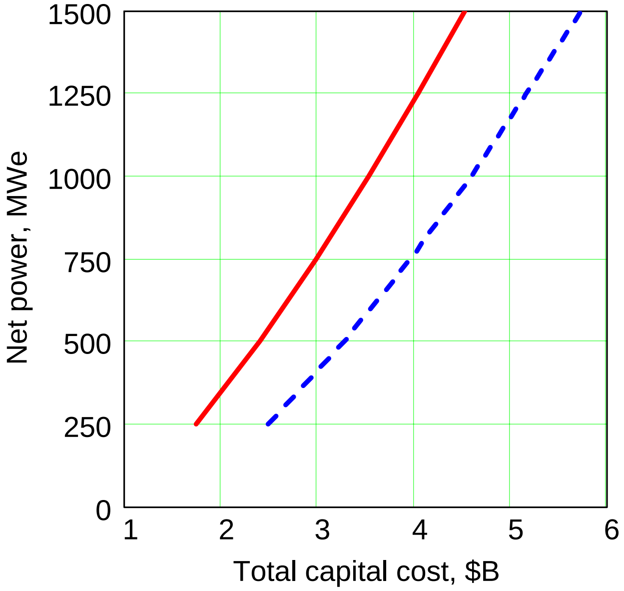

Fig. 5. Net power generated by FI (solid) and CI (dashed) power plants as a function of total capital cost.

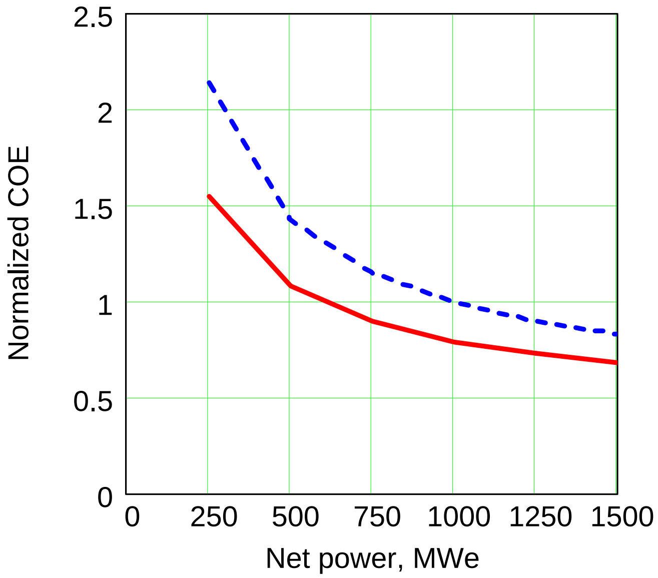

Fig. 6. Normalized COE as a function of plant net power for FI (solid) and CI (dashed) plants.

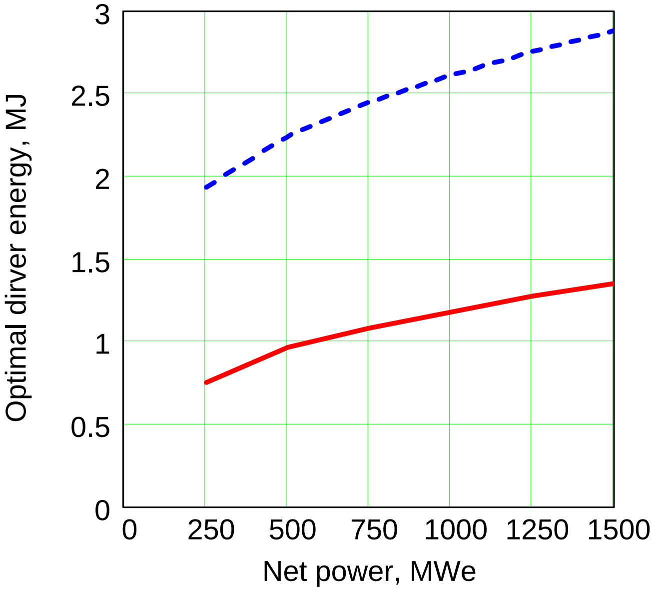

Fig. 7. Optimal driver energy as a function of net power for FI (solid) and CI (dashed) plants.

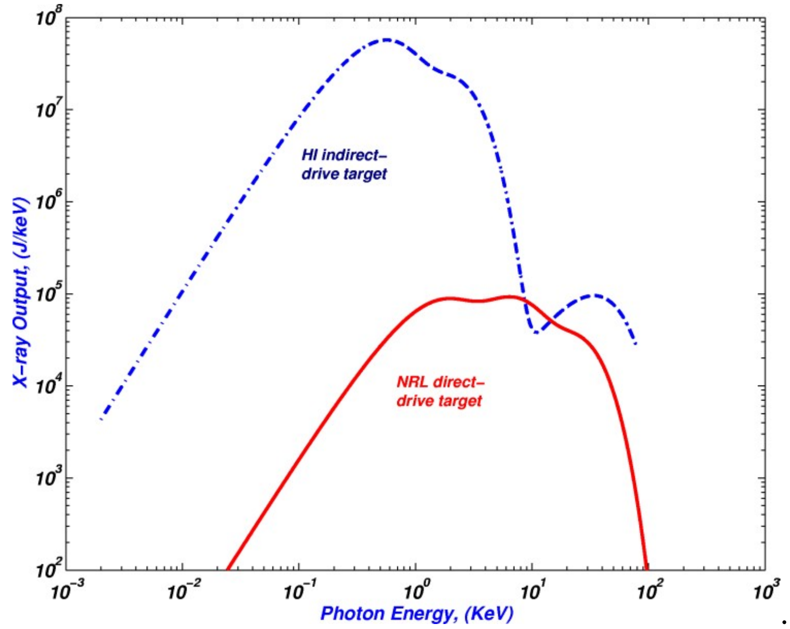

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Fig. 8. X-ray output spectra for direct and indirect drive central ignition targets and for a direct drive cone focus fast ignition target.

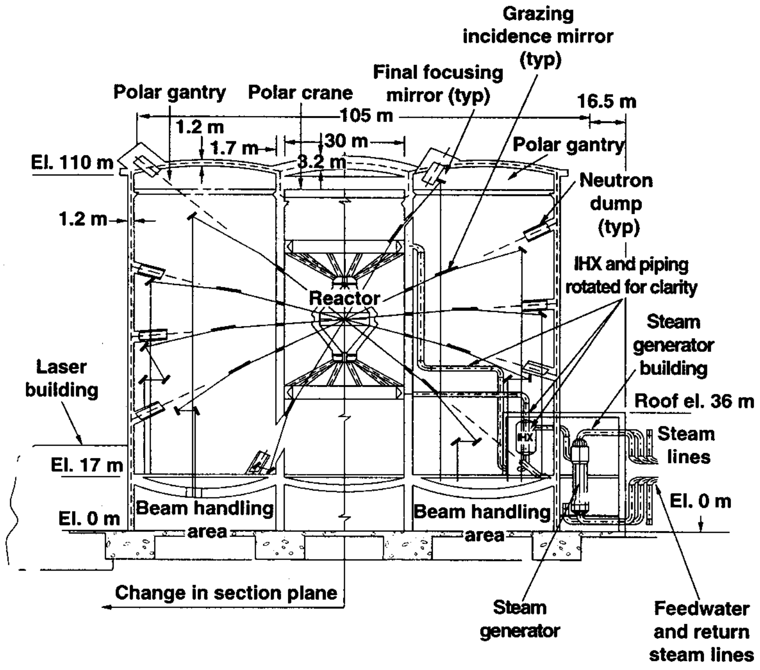


Fig. 9. The Sombrero chamber concept can accommodate all target concepts that require illumination from a large number of angles.

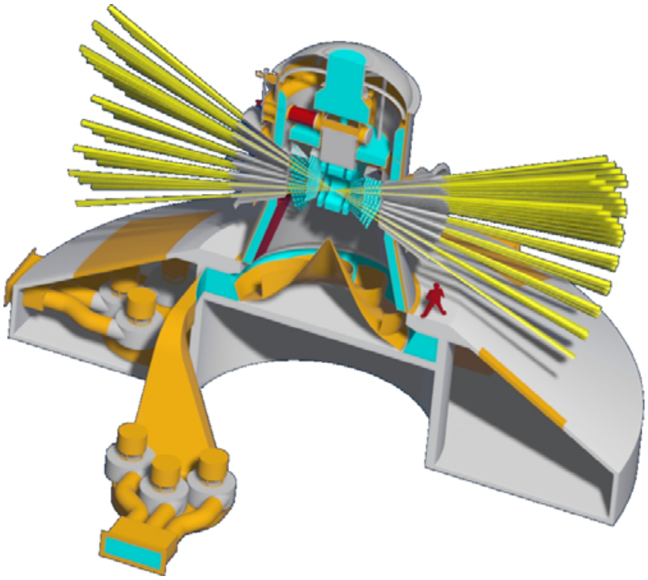


Fig. 10. The Robust Point Design chamber (based on the HYLIFE-II chamber) is shown with two-sided illumination by 120 ion beams. A thick layer of liquid protection is provided by pumping molten salt (Flibe) through the chamber.

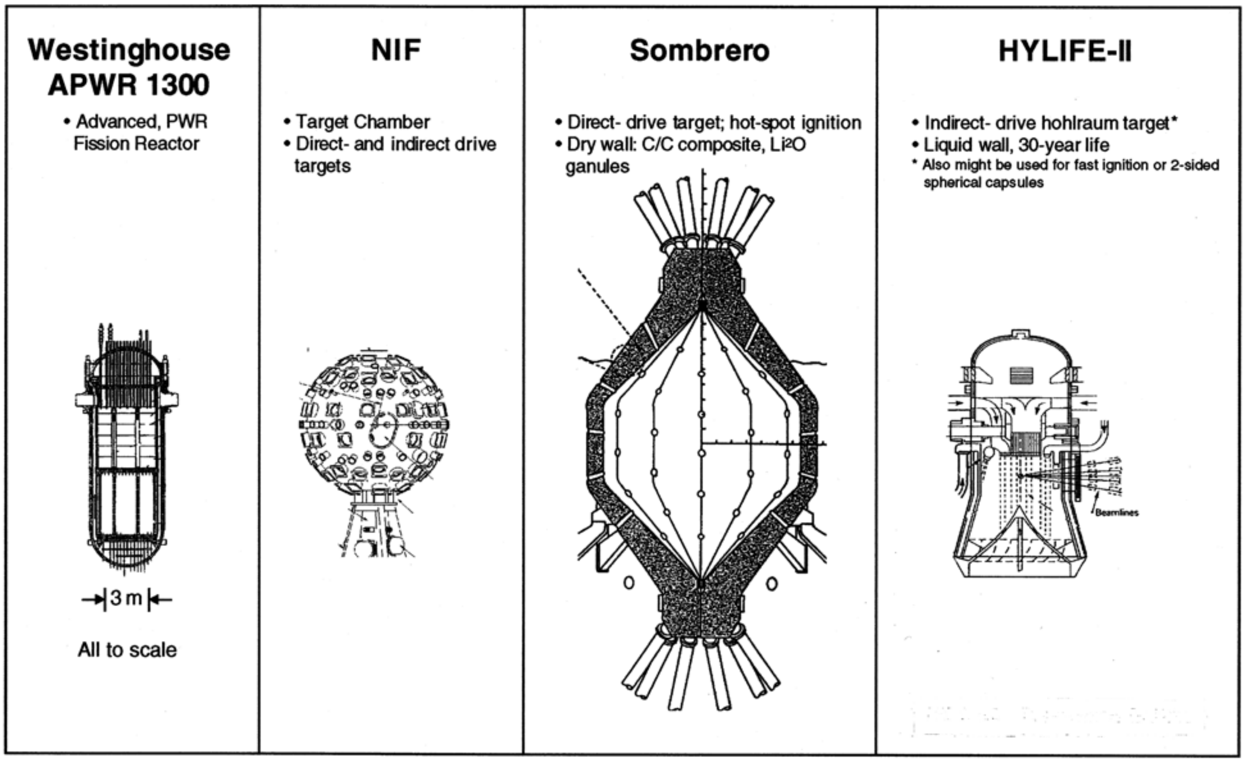


Fig. 11. Scale drawings of two IFE chamber concepts compared to the NIF target chamber and a common fission reactor core.

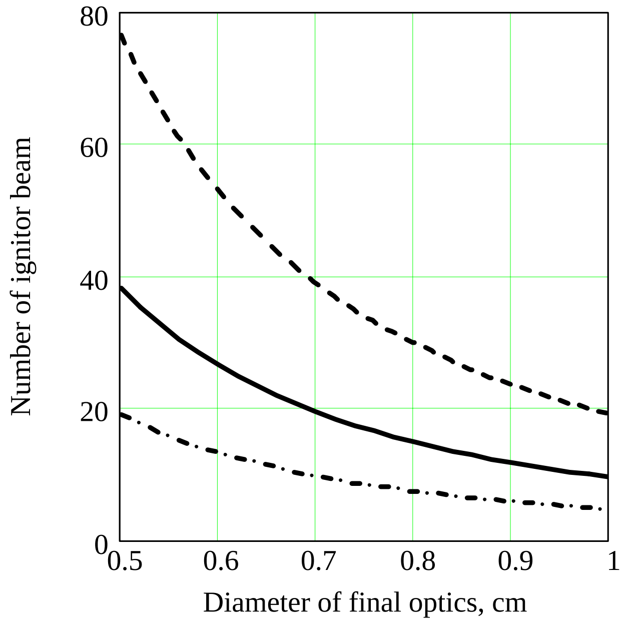
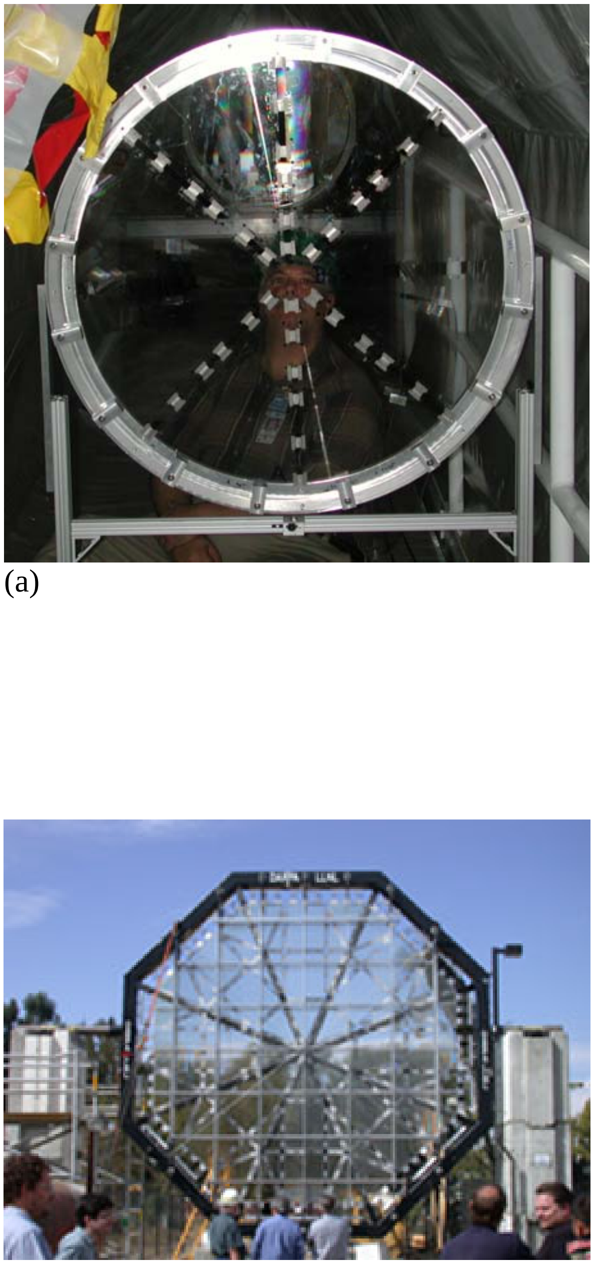


Fig. 12. Number of ignitor beams required vs. final optic dimensions for 75 kJ ignitor energy coupled to compressed fuel core. Solid line = 25% coupling efficiency and laser damage limit of 4 J/cm^2; dashed = factor of two lower coupling efficiency (12.5%) or factor of two lower laser damage limit (2 J/cm^2); dash-dot line = factor of two higher coupling efficiency (50%) or factor of two higher laser damage limit (8 J/cm^2).



(a)

(b)

Fig. 13. (a) An 80 cm diameter, 1 mm thick Fresnel lens was fabricated in the Eyeglass project t LLNL. (b) An even larger Fresnel lens array was later fabricated.

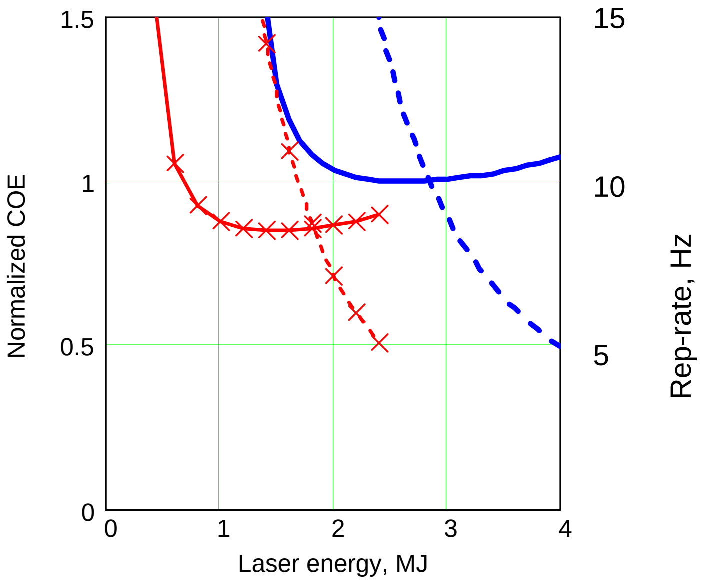


Fig. 14. COE for fast ignition compared to central ignition assuming a 40% dud rate for FI targets.