Target Design Activities for Inertial Fusion Energy at Lawrence Livermore National Laboratory

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We studied a variety of targets to be driven by ion beams or lasers in the past year. In order to relax target fabrication requirements, expand the allowed beam phase space volume and meet some radiological safety requirements, we continued to extend the set of the distributed radiator target designs for heavy ion beams. The hydrodynamic stability of a high gain directly driven laser target recently proposed at the Naval Research Laboratory has been studied. Because target chambers are sensitive to the x-ray spectrum as well as the composition and energy of the capsule debris we also present these for this target. A novel implosion scheme for the Fast Ignitor fusion scenario that minimizes the amount of coronal plasma that the igniting laser beam must penetrate is described. We describe recently derived scaling laws that relate the minimum value of the incoming fuel kinetic energy to the peak drive pressure, the fuel adiabat and the implosion velocity for capsules that use the kinetic energy of the implosion to heat the hotspot to ignition temperatures.

1. Introduction

We are making progress on targets for inertial fusion energy on three fronts: we are working to understand and relax driver and fabrication requirements for all three mainline drivers. We are pursuing advanced concepts, such as fast ignition, which if feasible, could significantly improve the attractiveness of an inertial fusion energy powerplant. Finally, we are working on enhancing our fundamental understanding of inertial confinement fusion.

We studied a variety of targets to be driven by ion beams or lasers in the past year. In order to relax target fabrication requirements, expand the allowed beam phase space volume and meet some radiological safety requirements, we continued to extend the set of the distributed radiator target designs for heavy ion beams. The hydrodynamic stability of a high gain directly driven laser target recently proposed at the Naval Research Laboratory has been studied. Because target chambers are sensitive to the x-ray spectrum as well as the composition and energy of the capsule debris we also present these for this target. A novel implosion scheme for the Fast Ignitor fusion scenario that minimizes the amount of coronal plasma that the igniting laser beam must penetrate is described. We describe recently derived scaling laws that relate the minimum value of the incoming fuel kinetic energy to the peak drive pressure, the fuel adiabat and the implosion velocity for capsules that use the kinetic energy of the implosion to heat the hotspot to ignition temperatures.

2. Understanding and Relaxing the Constraints that Baseline Targets Impose in a Reactor Environment

Since its beginnings several years ago[1,2,3] , the distributed radiator target for heavy ion fusion has evolved in a number of ways. A multi-beam version[4,5,6] in a "close-coupled arrangement" produces, in calculations integrated from ion beam injection through thermonuclear burn, 420 MJ when driven with 3.3 MJ of 3.5 GeV Pb ions. An engineering test facility(ETF) scale of this target has shown gain 90 with input energy 1.7 MJ, also in integrated ignition calculations. Simple models predict substantial gain with input energy under 1 MJ. In the less tightly coupled arrangements these designs have shown sufficient flexibility to accommodate variations in ion beam range of more than two(with some cost in gain) and variations in the relative importance of the Bragg peak in the stopping power profile.

Recently, we have expanded the target parameter space to relax outside systems requirements. We have found a new mixture of materials for hohlraum walls that combines high wall opacity with low neutron induced residual radioactivity. Formerly, our hohlraum walls were composed of a 50-50 mixture of gold and gadolinium. This mixture was used so that spectral gaps in the opacity of one material were filled in by the peaks of the other. This choice is, of course, not unique. We chose to find a mixture that did not include gold, because the residual radioactivity induced in gold by 14 MeV neutrons is quite high compared to that in other materials. We searched for low wall loss materials that also had residual induced radioactivity down two orders of magnitude from gold. Table 1 shows the relative wall loss for a number of normalized to the Au-Gd mix.

Most of the distributed radiator designs require low-density but high atomic number materials. These will be difficult to fabricate into hohlraums. Recent calculations have shown that the low-density walls assumed in the original designs are not required.

A significant uncertainty in accelerator driven fusion is the size of the beam spot at the target. The original distributed radiator target shown in figure 1 required 5.9 MJ of beam energy to produce gain 68. This target required and array of individual spots where 95% of the charge was contained in an ellipse with semi-minor axis 1.8 mm and semi-major axis 2.7 mm leading to an effective radius of 2.7 mm. This original design places these beams around a beam block. A hybrid design shown in figure 2 accepts energy deposited behind the beam block/shine shield that is then radiatively transported to the main hohlraum volume and finally to the capsule. This arrangement alone does not produce adequate symmetry. A radiation shim is applied to the capsule in order to control the early time P_4 asymmetry. At late times, the radiation accepting surface of the capsule has imploded and radiation transport smoothing is adequate to produce good symmetry. This design requires 6.7 MJ to produce gain 58(still adequate with 25% efficient drivers) but with spots having semi-minor axis 3.8 mm and semi-major axis 4.5mm or effective radius 4.5 mm. Hence, we have achieved a 66% increase in beam radius with only a 14% increase in beam energy. We continue to consider other designs that can accept larger beam spots: a "tuna can" design with large radius but decreased length and designs in which the beams are incident through the cylindrical surface of the target not the ends.

We have calculated in multimode implosion calculations the stability of the capsules with beryllium ablators assumed in the integrated calculations of target performance. These capsules ignited in the Rayleigh-Taylor calculations with surface finishes an order of magnitude worse than the NIF specification. When capsules ignite on the NIF, these reactor-scale capsules will be shown to be quite robust. However, we currently do not know how to mass-produce and fill with DT capsules with beryllium ablators. There are concrete schemes for mass-producing capsules with CH ablators. In addition, diffusion-filling these capsules with DT will take less time than beryllium capsules would. This leads to lower tritium inventory for a reactor. So we studied the stability of these capsules. In figure 3, we show such a capsule design, a characteristic density plot near ignition time, and yield as function of ablator roughness. The finish used for CH capsules tested on NOVA[7] was 10 nm. Therefore, we think there is plausible development path to produce capsules for HIF.

Most designs for capsules directly illuminated with laser beams require approximately symmetric illumination. This leads to an approximately uniform density of laser entrance holes in the target chamber. It is not clear that thick liquid wall protection schemes are consistent with this geometry. If a gas-protected drywall scheme like the Sombrero design[8] is used, it is important to understand the capsule output. Figure 4 shows the capsule designed at the Naval Research Laboratory(NRL)[9] whose output we are studying. Table II shows how the output is composed. Figure 5 shows the output spectra.

We are also studying the stability of this capsule. The novel feature of this capsule is foam ablator overcoated with a thin layer of gold. The gold is designed to radiate photons that will selectively preheat the ablator. The ablator will be on a high adiabat to help stabilize the implosion, while the fuel will be on a low adiabat to achieve high gain. Previous designs placed the fuel and ablator on a high adiabat in order to achieve stability at the cost of lowered gain. We are currently modeling the NRL design with 2-D calculations as well as an application of the Betti-Goncharov(BG)[10] model. Figure 6 shows the prediction of the BG model as a function of mode number for this capsule and an indirectly driven HIF design, together with growth factors for the indirectly driven design calculated with a 2-D hydrodynamics code. The directly driven capsule shows similar growth to the indirect drive design at low modes, but higher growth at high mode number. Hence, the directly driven design is more liable to failure by shell break-up during the implosion. These model results need to confirmed in detailed hydrodynamic simulations.

3. Advanced Fusion Schemes

We continue to develop fusion schemes that may lead to lower cost energy. The Fast Ignitor fusion scheme[11] has several phases(see figure 9). First, the fusion fuel is compressed to high density. Then, through ponderomotive hole-boring, or some other scheme, the distance between critical density and the ignition region is reduced. Finally, a very high intensity beam of external energy (usually considered to be a laser) supplies the required ignition energy in a hotspot disassembly time. The scheme claims relaxed implosion requirements and substantially improved gains compared capsules that are ignited by the stagnating kinetic energy of the implosion. A critical issue for this scheme is the efficiency with which the beam energy is coupled to the compressed fuel. Recent experiments have inferred approximately 50% of incident laser light coupled to forward-going hot electrons. If the distance between the ignition region and the hot-electron source is comparable to the spot size, then good coupling can be hoped for. Although early experiments[12] showed that hole-boring through critical density plasmas is possible, hole-boring and efficient laser propagation through many spot diameters of plasma many times critical density is still problematic. A cone focus geometry(see figure 7) where the ignition laser has direct access to the ignition region with no intervening coronal plasma may solve this problem. In this geometry, a high-density conical shell is inserted into the spherical shell composing the implosion capsule. When the capsule is driven with a radiation temperature profile chosen to drive NIF capsules, the converged configuration shown in figure 8 is produced. The total fuel column density is 2 gm/cm^2 so high quality implosions are possible even with the large perturbation in the implosion capsule. The high density region is about 90 microns from the end of the cone, where the high intensity laser beam can couple to the shell. The range of the electrons produced in the interaction is large compared to the thickness of the cone at the apex, so the electrons can propagate to the fuel. Variations in capsule design that will reduce the ignition region-apex distance are under study.

4. Ignition Scaling Laws

The attractiveness and feasibility of an inertial fusion energy power plant is strongly affected by the requirements of the capsule for achieving ignition and high gain. Thus, a greater understanding of these requirements will undoubtedly be useful in the optimization of an eventual reactor.

We have recently completed a study[13] of the minimum energy needed for ignition in the absence of capsule imperfections. The minimum fuel energy is found to scale with various capsule parameters (i.e., the implosion velocity (v), the fuel adiabat ($\alpha_{\mathrm{if},}$ the ratio of fuel pressure to Fermi degenerate pressure at the time of peak implosion velocity), the drive pressure(P)) in the following way:

$$E_{ign}(kJ) = 50.8\ \alpha_{if}^{1.88} \left(\frac{\mathrm{v}}{3*10^{7}\,\mathrm{cm/sec}}\right)^{-5.89} \left(\frac{P}{100\,\mathrm{MB}}\right)^{-0.77}$$

This study resolves a discrepancy in previous studies[14,15], regarding the dependence of the ignition energy on the drive pressure. If we hold P constant this leads to the result of Levedahl and Lindl, $E \sim \alpha_{\mathrm{if}}^{1.9}\mathrm{v}^{-5.9}$ and if we take $P \sim \alpha^{-1.5}\mathrm{v}^{5}$ as Basko and Johner used in their scaling we obtain their result, $E \sim \alpha_{\mathrm{if}}^{3}\,\mathrm{v}^{-9.6}$. This generalized scaling law will be useful in extrapolating from NIF scale to reactor scale capsules.

When the inevitable perturbations are included the capsule can fail to ignite due to the mix of cold fuel into the hot spot. Additional implosion velocity (above the minimum given above) can be used to overcome this mix however this additional implosion velocity is provided at the cost of having a more unstable implosion. We are currently working to understand this optimization, so we can design the most robust capsule possible for a given driver energy.

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References

1. TABAK,M.,et al,, *Nuclear Fusion* **38**,4(1998)509.
2.TABAK,M.,et.al, *Physics of Plasmas* **5**,5 pt2 Special issue(1998)1895.
3. TABAK,M. and CALLAHAN-MILLER,D.A., *Nuclear Instruments &Methods A* **415**(1998)75-84.
4. CALLAHAN-MILLER,D.A and TABAK,M., *Nuclear Fusion* **39**(1999)883-891.
5. CALLAHAN-MILLER,D.A and TABAK,M, *Nuclear Fusion* **39**(1999)1547-1556.
6. CALLAHAN-MILLER,D.A and TABAK,M, *Physics of Plasmas* **7**(May 2000)2083-2091.
7. MARINAK,M.M., et. al.,*Physics of Plasmas* **3**(1996)2070.
8.SVIATOSLAVSKY,I.N.,et.al,*Fusion Technology* **21**(1992)1470.
9. BODNER,S.E.,et.al., *Physics of Plasmas* **7**(2000)2298.

10. BETTI,R.,et.al.,*Physics of Plasmas* **3**(1996)2122.
11. TABAK,M.,et al., *Physics of Plasmas* **1** (May,1994)1626-1634.
12. YOUNG,P.E.,et.al., *Phys. Rev. Lett.* **75**(August 7,1995) 1082-1085.
13. HERRMANN,M.C.,TABAK,M.,and LINDL,J.D., to be published.
14. LEVEDAHL,W.K. and LINDL,J.D., *Nucl. Fusion* **37** (1997) 165.
15. BASKO,M.M. and JOHNER,J., *Nucl. Fusion* **38** (1998) 1779.

Table 1

Relative wall loss normalized to Au/Gd, opacity(cm^2/g) and internal energy(MJ/g) for various material compositions when driven with a radiation temperature history suitable to drive a capsule.

Material	κ_R	Internal Energy	E_{wall}
Au/Gd(50:50)	2480	14.8	1.00
Au	1550	14.2	1.25
Pb	1640	13.9	1.28
Hg	1580	14.1	1.26
Ta	1340	14.5	1.25
W	1370	14.4	1.25
Pb/Ta(50:50)	2060	14.3	1.08
Pb/Ta(70:30)	2160	14.1	1.06
Hg/Xe(50:50)	2100	15.1	1.18
Pb/Ta/Cs(50:20:30)	2520	14.7	1.01
Pb/Ta/Cs(45:20:35)	2560	14.7	1.01
Hg/Ta/Cs(45:20:35)	2520	15.1	1.03
Hg/W/Cs (45:20:35)	2370	14.9	1.04
Pb/Hf(70:30)	2203	14.1	1.04
Pb/Hf/Xe	2554	14.8	1.00

Table II: Division of output for NRL design

Component of output	Energy(MJ)
xrays	2.1
neutrons	109
Charged burn products	18.1
Debris ions	24.9
Total output	154

Figure Captions

1. Original multibeam distributed radiator design. One quadrant of the hohlraum and capsule. The target is reflected about the z=0 plane and rotated about the r=0 axis. The hohlraum case extends out to 1.8 cm. The materials and densities(g/cm^3) are: A,DT,0.0003; B,DT,0.25; C,$Be_{0.995}Br_{0.005}$,1.845; D, Au,0.032;E,$CD_2Au_{0.03}$,0.011;F,Fe,0.064;G,Fe,0.083; H,$CD_2Au_{0.03}$,0.032; I,AuGd,0.1;J,AuGd,0.26;K,AuGd,0.099;L,AuGd,13.5(20μm thick); M,Al,0.055;N,AuGd,0.099;1.0,0.5(from inside hohlraum to outside);0,D_2,0.01.
2. Cartoon of hybrid target. The placement of the shine shield tunes the P_2 asymmetry, while the radiation shims near the target control the early time P_4.
3. A) Reactor scale implosion capsule with CH ablator;B) density plot from 2-D multimode calculation near igntion time;C, capsule yield as a function of initial surface roughness.
4. Direct drive capsule designed at NRL.
5. A) Debris spectra calculated to be produced by the capsule of figure 4;B) burn particle spectra.
6. Betti-Goncharov growth-factor predictions for capsules shown in figures 3A(solid line) and 4(dashed line), together with growth factor calculated in 2D for capsule of figure 5A(solid points).
7. A cone focus geometry inserts a high density cone into the implosion capsule allowing ready access of the high intensity beam to the compressed fuel.
8. Density of matter after cone-focus implosion.
9. The Fast Ignitor scheme has 3 phases: capsule implosion,removal of coronal plasma, and ignition with a high intensity beam.

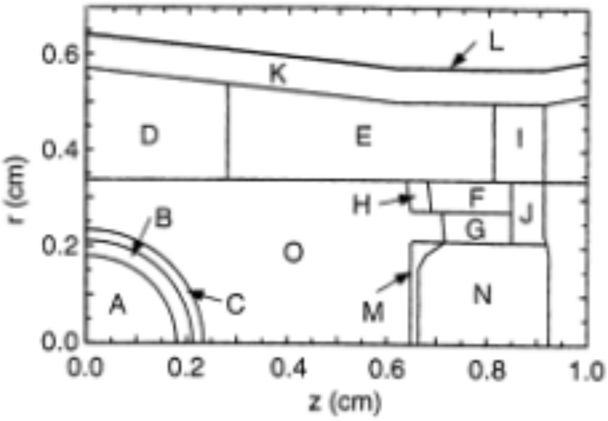


Figure 1

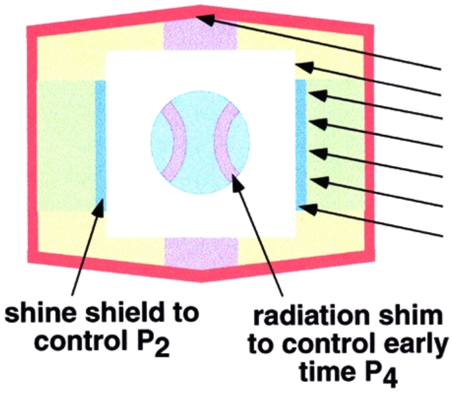


Figure 2

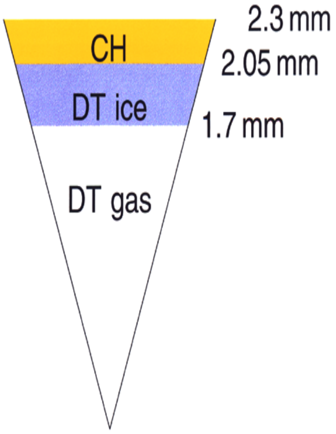


Figure 3A

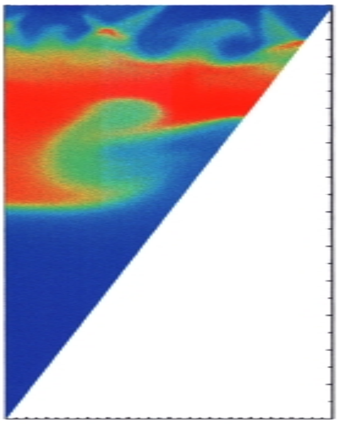


Figure 3B

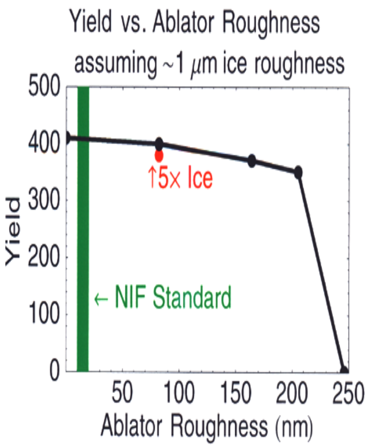


Figure 3C

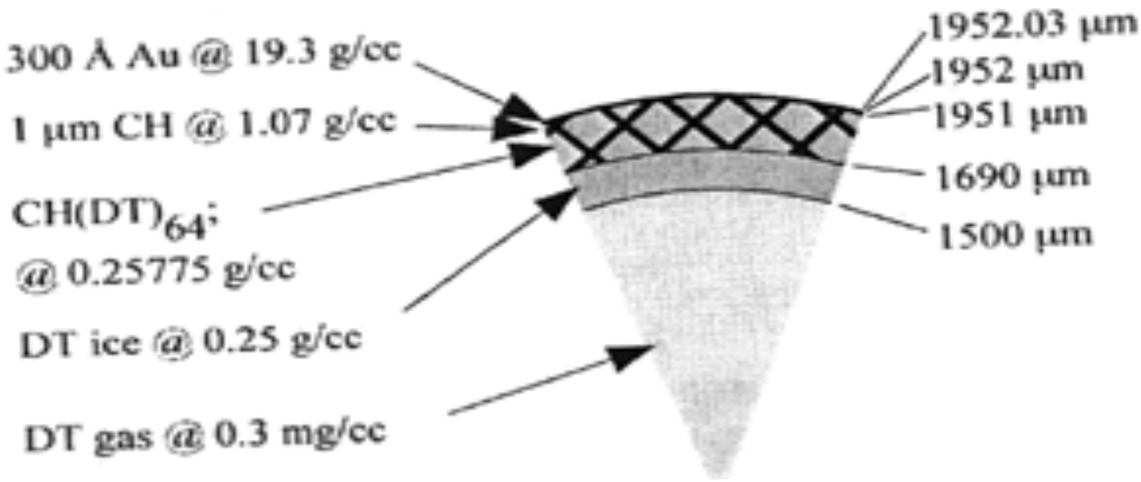


Figure 4

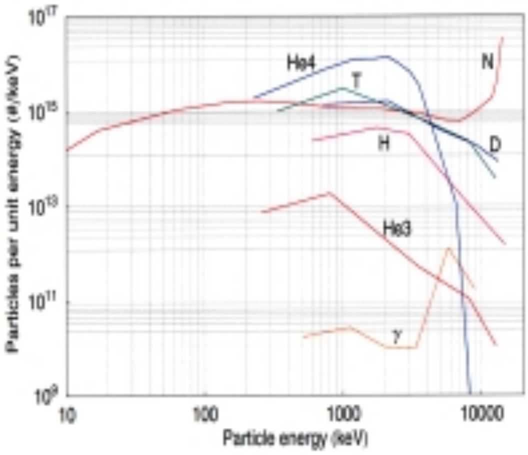


Figure 5A

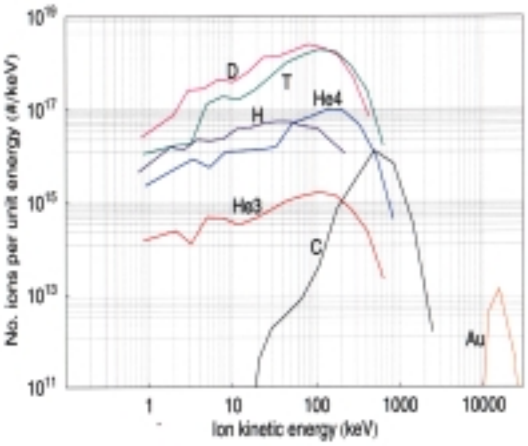


Figure 5B

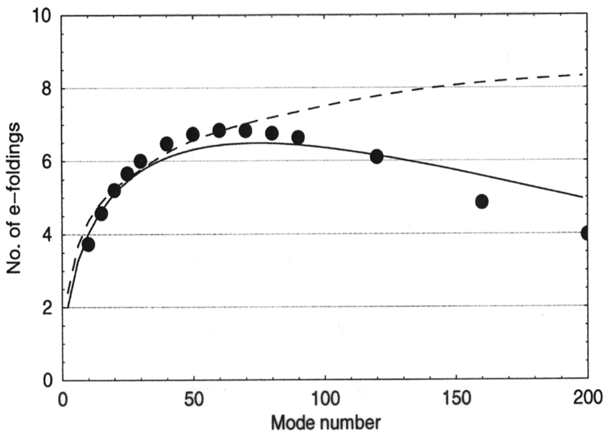


Figure 6

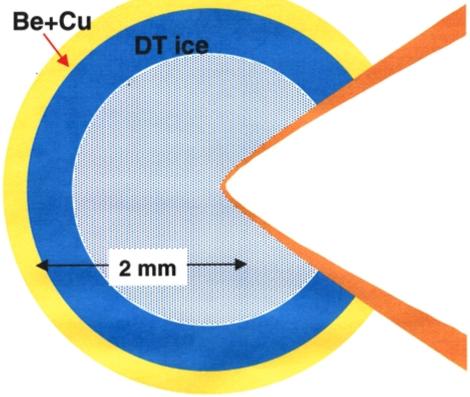
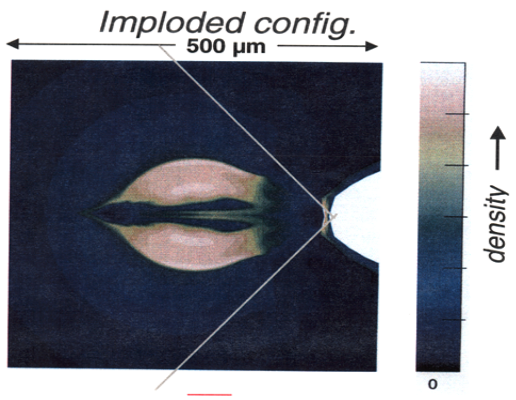
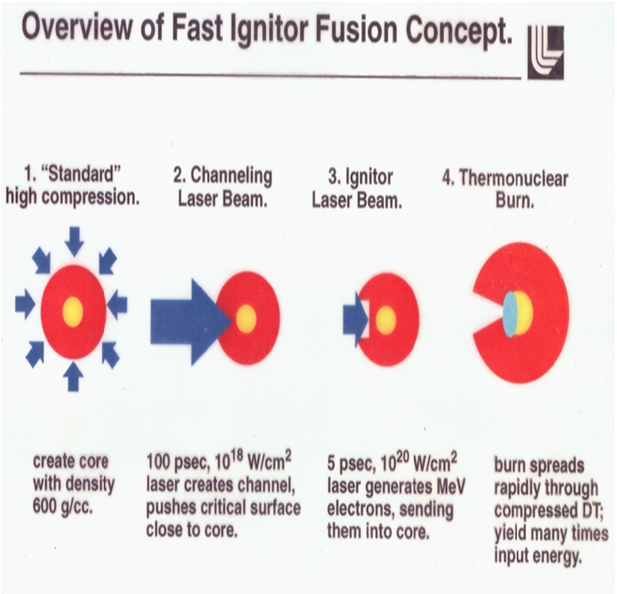


Figure 7



$<\rho R>_{DT}=2.02\ g/cm^2$

blob is ~90 µm away.



Overview of Fast Ignitor Fusion Concept.

1. "Standard" high compression.	2. Channeling Laser Beam.	3. Ignitor Laser Beam.	4. Thermonuclear Burn.
create core with density 600 g/cc.	100 psec, 10^{18} W/cm^2 laser creates channel, pushes critical surface close to core.	5 psec, 10^{20} W/cm^2 laser generates MeV electrons, sending them into core.	burn spreads rapidly through compressed DT; yield many times input energy.