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# On the path to fusion energy

## Teller lecture 2005

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**Abstract.** There is a need to develop alternate energy sources in the coming century because fossil fuels will become depleted and their use may lead to global climate change. Inertial fusion can become such an energy source, but significant progress must be made before its promise is realized. The high-density approach to inertial fusion suggested by Nuckolls et al. leads reaction chambers compatible with civilian power production. Methods to achieve the good control of hydrodynamic stability and implosion symmetry required to achieve these high fuel densities will be discussed. Fast Ignition, a technique that achieves fusion ignition by igniting fusion fuel after it is assembled, will be described along with its gain curves. Fusion costs of energy for conventional hotspot ignition will be compared with those of Fast Ignition and their capital costs compared with advanced fission plants. Finally, techniques that may improve possible Fast Ignition gains by an order of magnitude and reduce driver scales by an order of magnitude below conventional ignition requirements are described.

**PACS.** 52.58.Hm Heavy-ion inertial confinement – 52.57.Fg Implosion symmetry and hydrodynamic instability – 52.57.Kk Fast ignition of compressed fusion fuels

Edward Teller, whom we honor and remember with the Teller Medal, made seminal contributions in many areas of physics such as nuclear physics (Gamow-Teller [1] weak transitions), condensed matter physics (Lyddane-Sachs-Teller [2] relation), atomic physics (Jahn-Teller [3] effect) and many more. He is, perhaps, best known for demonstrating inertially confined thermonuclear fusion on earth in the form of thermonuclear explosives. That work showed that inertial fusion will work in principle, although its practical application as an energy source will require significant reductions in scale. The International Thermonuclear Experimental Reactor (ITER) will provide the in principle demonstration for magnetically confined fusion. Prof. Teller's work already reduced the scale required for fusion from thousands of kilometers (white dwarfs) to of order a meter. Use of fusion as a terrestrial energy source requires a further reduction in scale to the millimeter scale — a much smaller reduction than Prof. Teller already accomplished!

Can we make inertial fusion relevant to the energy needs of the world? We will need new energy sources in the coming century to replace petroleum based fuels and possibly all carbon based fuels. Some estimates suggest that petroleum and natural gas reserves will be exhausted in the next 50 years. Coal, tar sands and oil shales may extend the supply of carbon-based fuels to centuries. However, the role of atmospheric $CO_2$ in global climate change may preclude continuing use of fossil fuels without sequestration. Strategies are being developed for collecting the $CO_2$ produced by combustion and injecting it into deep wells or deep under the sea. At this time there is no consensus on the practicality of this approach.

A number of energy source alternatives to fossil fuels exist and produce net power. All of them have difficulties to overcome before they are ready to replace fossil fuels. Solar energy is a diffuse energy source requiring collectors of large area and some form of energy storage. Wind energy is growing as an adjunct to baseload electricity, but suffers from extreme variability. Hydroelectric power is a traditional low cost source of energy, but most good sites are taken and it is unlikely that there will be substantial growth in this area. Fission can produce competitively priced electricity. However, because of concerns about accidents, nuclear waste disposal and nuclear weapons proliferation, fission has had difficulty gaining public acceptance, at least in the United States. In addition, fission will require reprocessing of the spent fuel to stretch the supply of low cost uranium to centuries and breeding to stretch the supply to a few millennia. Both of these technologies add risk to fission technology. Low density supplies of uranium and thorium in granite or seawater could supply fission fuel for billions of years at higher cost.

Fusion is a cleaner form of nuclear power which can contribute to the world's energy needs. There is adequate low cost lithium for tens of thousands of years of deuterium-tritium fusion and adequate deuterium in the

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oceans for billions of years of deuterium fusion. However, fusion does not at this time produce net power, while the energy alternatives are existing technologies whose efficiencies will improve with continuing development. Fusion's acceptance in the marketplace will rely on it becoming cost competitive to the other energy sources. If consumer power is produced through a conventional thermal conversion cycle, then competitive fusion power requires that the fusion specific cost will be comparable in cost to the fuel cycle costs and other externalities (like waste disposal and proliferation resistance). This implies, for inertial fusion, that the driver cost is small compared to the conventional balance of plant. This places the requirement that the target design must achieve high gain at low driver energy.

Nuckolls et al. [4] showed that by compressing fusion fuel to high density the driver energy required to a achieve high gain can be substantially lowered. High fuel density requires high implosion velocity. Limitations on drive intensity due to focusing limitations (heavy ion beam or $z$-pinch driven fusion) or plasma instabilities (lasers) lead to large convergence ratios (CR) as well as large in-flight-aspect ratios (IFAR). The large CR's and associated IFAR's mean that fuel assembly depends strongly on hydrodynamic stability and illumination symmetry. Much of the research in this field has revolved about resolving these issues. In this paper, I will discuss how I, along with many others, have contributed to advancing inertial fusion as a possible energy source.

The Halite/Centurion (H/C) program was a collaborative effort by Lawrence Livermore National Laboratory and Los Alamos National Laboratory to explore fundamental issues related to inertial fusion using nuclear explosives. The energy rich environment allowed us to study these issues long before laboratory drivers would be available for this work. For many of us on the design team, this was our first practical exposure to inertial fusion: truly on-the-job training. Henry D. Shay, the group leader, had significant experience in nuclear design and inertial fusion. A. Ronald Thiessen was a co-author of the original Nature paper that started the field. The rest of us had experience ranging from less than Shay or Thiessen to none at all. The Livermore team members included at various times Charles Orth, Richard Sacks, Thomas Dittrich, Heiner Meldner, Stephen Weber, Manoj Prasad and Steve Haan (who later became group leader). Very rapid progress was made and led to the assessment that fundamental issues necessary for successful laboratory inertial fusion had been demonstrated. These results were an important ingredient in the decision to go forward with the National Ignition Facility (NIF).

In order for the direct drive approach to laser fusion to be viable, the implosions must be hydrodynamically stable. Specifically, we want the implosions to be stable for the lowest possible incident laser intensity for several reasons: the peak useful intensity is limited by the reduction of the laser-plasma coupling due to inverse bremsstrahlung and by the increase in growth of plasma instabilities. Also the hydrodynamic efficiency, for fixed implosion velocity, is inversely correlated with the laser intensity [5]

$$\eta_{hydro} \sim v_{exh}^{-1} v_{imp} \quad \text{and} \quad v_{exh} \sim I^{1/3},$$

where $\eta_{hydro}$ is the hydrodynamic efficiency, $v_{exh}$ is the sound speed of the ablated plasma, $v_{imp}$ is the implosion velocity of the shell and $I$ is the laser intensity.

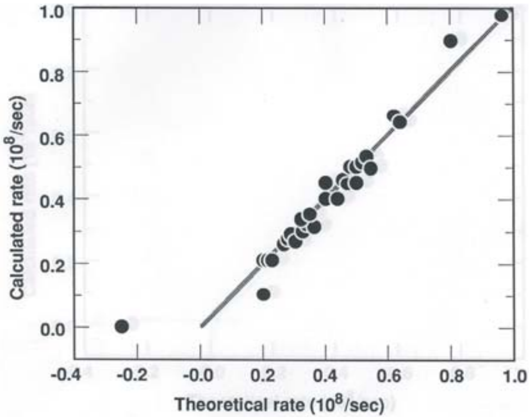


**Fig. 1.** Comparison of growth rates measured in LASNEX calculations with those of the Takabe formula.

The in-flight-aspect-ratio (IFAR) is positively correlated with the hydrodynamic efficiency

$$IFAR \sim I^{-4/15} \sim (v_{abl} v_{exh})^{-1} v_{imp}^2,$$

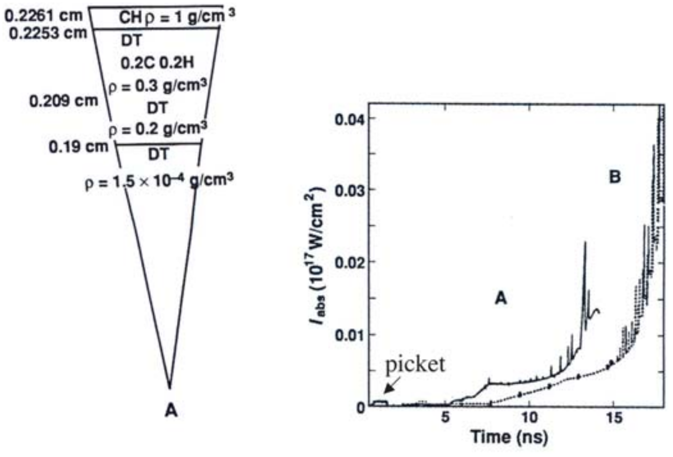
where $v_{abl}$ is the speed with which the ablation front eats into the ablator.

In practice, for implosions using 2–3 MJ of laser energy and a maximum intensity of about $10^{15}$ W/cm$^2$ of 0.35 micron laser light, the peak IFAR approaches 100. This is a very thin shell and would survive little instability growth. To make further progress we need to understand how the Rayleigh-Taylor instability grows in time. H. Takabe and coworkers had performed an eigenvalue analysis of the growth of instability when a slab or thin shell is driven by an energy source where the heat is transported by electron conduction. Summarizing a number of numerical simulations, they obtained the following formula for the growth:

$$\gamma = \alpha (kg)^{1/2} - \beta k v_{abl},$$

where $\gamma$ is the growth rate, $k$ is the instability wave number, $g$ is the shell acceleration, $\alpha$ is approximately 0.9 and $\beta$ is a constant between 3 and 4.

David Munro, John Lindl and I verified this formula (see Fig. 1) in full 2D initial value hydrodynamic calculations using the computer code LASNEX. This work demonstrated that one could reduce the instability rate by increasing the ablation velocity relative to the acceleration. The mass ablation rate, $\dot{m} = \rho v_{abl}$, is approximately invariant to the density, $\rho$. If $\rho$ can be reduced, $v_{abl}$ will be increased. $\rho$ will be reduced if its entropy can be increased. However, if the entropy of the fuel is increased, it will be more difficult ignite and the burn efficiency will be reduced. Can we increase the entropy in the ablator to



(a) (b)

**Fig. 2.** (a) Pie diagram of directly driven capsule; (b) absorbed intensity as a function of time for two designs. The curve labeled “A” is associated with the capsule shown.

improve its stability properties while maintaining the low entropy state of the fuel?

This adiabat shaping can be accomplished by replacing the long foot of the drive pulse, used in conventional designs, with a short, high-pressure picket that contains the same impulse as the conventional foot. This picket will launch a decaying shock [6] so that there is a large entropy jump on the outside of the ablator, but little change in entropy in the fuel. Figure 2 shows a target design [7] together with the laser intensity profile (A) driving the capsule. The spikes in the figure reflect zone-popping. The capsule absorbed 1.7 MJ and yielded about 160 MJ. The worst mode grew 8 efoldings, a significant reduction from the 12–13 efoldings of previous calculations. The peak IFAR was around 40. Capsules using a long, low foot and driven to a comparable implosion velocity, $3.6 \times 10^7$ cm/s, have IFAR’s approaching 100. Charles Verdon, then of the University of Rochester, independently developed similar designs at about the same time (1990). Recently, this idea of adiabat shaping has been revived by Betti and Goncharov (2003) [8] and has led to targets with gain between 100 and 150 for about 3 MJ of laser energy.

For directly driven targets, symmetry is achieved by proper beam placement and shape. For indirectly driven targets the symmetry of radiation incident on an implosion capsule is the result of more complicated set of factors. These effects are and were calculated in radiation-hydrodynamic codes like LASNEX as well as with view-factor codes like WALLE or GERTIE. It is valuable to develop simple models that can guide design.

Joseph Green [9] of RDA developed analytic formulae for the smoothing of radiation flux asymmetries as the radiation is transported from a spherical wall to a concentric spherical capsule in the limit where the ratio of radii is infinite. S. Haan [10] extended these results to arbitrary radii ratios numerically. An important result was that asymmetries described by Legendre polynomials with mode numbers above 3 are rapidly smoothed as this ratio increases.

**Fig. 3.** (Color online) Distributed radiator heavy ion target design.

The source functions describing the radiation emission at the hohlraum wall are determined by source placement and wall reradiation. J. Mark [11] showed that the contribution of a given source spot to a Legendre mode was proportional to the strength of the spot multiplied by the value of that Legendre mode at the spot position. Hence, by placing source rings at the zeroes of a Legendre polynomial that Legendre mode will not contribute to the source asymmetry. Mark also noted that if the ring strengths are assigned Gaussian weights, all Legendre modes with mode numbers below twice the number of rings will be zeroed. Tabak [12] generalized this scheme to include the effect of X-ray reradiation in hohlraums. A hohlraum can be treated as a uniformly bright surface perturbed by source spots, whose excess brightness is given by the average brightness divided by the number of times a photon is absorbed and re-emitted before it is finally absorbed, and entrance holes that act as negative sources with strength given by the average brightness. In this way a complicated radiation transport problem can be approximated as a set of algebraic equations. A similar scheme was later described in Lindl’s monograph [13].

This sort of reasoning was applied to the design of a number radiation driven systems starting with laser driven hohlraums and continuing to systems driven with heavy ion beams and $z$-pinches. Accelerators producing heavy ion beams are interesting drivers for inertial fusion energy because accelerators have been demonstrated to operate at high repetition rates and with driver efficiencies approaching 40%. Figure 3 shows a distributed radiator target driven by heavy ions. Figure 4 shows the energy density in a quarter of such a target. The energy was deposited near the zeroes of the Legendre polynomial, $P_4$ with a distribution approximately given by the weights appropriate to a Gaussian quadrature scheme. Maintaining the energy deposition in this fashion was the goal of the target design [14]. Hence the hohlraum was designed to be in approximate pressure balance so that the position of the radiation converters (where the ion beam energy was absorbed and heated material that then radiated) would be static. This reduced wall motion also resulted in somewhat lower energy loss to the hohlraum walls. D. Callahan [15] showed that targets of this sort could couple 27% of the incident ion beam energy to an implosion capsule with adequate symmetry to produce full yield. These

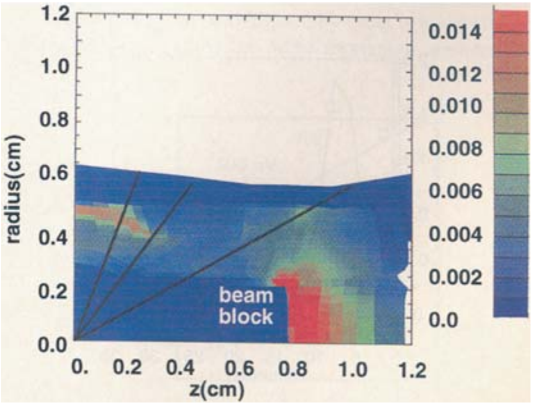


**Fig. 4.** (Color online) Deposited ion beam energy density in distributed radiator target. The lines mark the zeroes of the Legendre polynomials $P_4$ and $P_2$. In this example the injected beam has a top-hat profile and moves parallel to the symmetry axis.

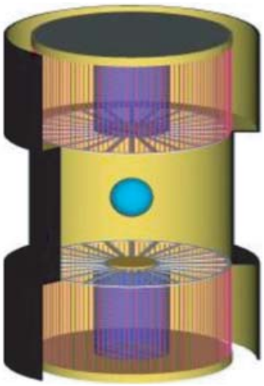


**Fig. 5.** (Color online) Target driven by 2-sided $z$-pinch.

"close-coupled" targets scale to gain 30 with 500 kJ of incident energy.

An interesting interplay between stability and symmetry conditions occurred in the design of a target [16] to be driven by dual $z$-pinches (Fig. 5). In this scheme two symmetrically arranged $z$-pinches (that can be driven by a single pulsed-power source) in primary hohlraums drive an implosion capsule in a secondary hohlraum. For systems where 10 MJ of electrical energy was delivered to each pinch, efficient coupling to the $z$-pinch load required that the implosion distance of the pinch and hence the primary hohlraum radius was of order a centimeter; as was the pinch length. X-rays are emitted when the high-$z$ pinch stagnates and heats. The X-ray emission region is separated from the implosion capsule by a shine shield so that the implosion capsule sees only flux that has been absorbed and re-emitted by the primary hohlraum walls. Implosion capsules absorbing between 1 and 2 MJ, yielding between 400 and 1000 MJ with radii between 0.27 and 0.37 cm are possible. Radiation transport adequately smoothes all modes above $P_2$ for the smaller capsules. While the larger capsules have a residual $P_4$ asymmetry that requires shading either in the plane of the shine shield/return current path or as a shim [17] near or on the implosion capsule.

The large hohlraum volume that helped to symmetrize the radiation incident on the capsule together with the pinch emission duration of approximately 10 nanoseconds leads to radiation temperatures of about 215 eV. This low temperature (designs for the National Ignition Facility use temperatures between 250 and 300 eV) meant that it would be difficult to drive the imploding shell to high velocity stably. As a guide to the implosion velocity required for ignition, we used the relation determined computationally by Levedahl and Lindl [18] (L&L):

$$E_{ign}(\mathrm{MJ}) = 0.025\eta_{hydro}^{-1}\alpha^{1.5}v_{imp}^{-5},$$

where $\alpha = 0.5P(\mathrm{Mbar})\rho^{5/3}(\mathrm{g/cm}^3)$. The large energy available from pulsed-power drivers therefore reduces the implosion velocity required for ignition. The implosion velocity is related to the radiation temperature and IFAR, $v_{imp}(\mathrm{cm/s}) = 5.1\times10^5\alpha^{0.6}$ IFAR $T^{0.9}(100\ \mathrm{eV})$, while the Rayleigh-Taylor growth rate for radiation driven capsules is approximately,

$$\gamma_{RT} = \sqrt{ka/(1+k\ell)} - kV_{abl}.$$

Hence, for fixed Legendre mode, $\ell$, the capsules driven to the minimum implosion velocity will have equal linear instability growth rates if $E_{ign} \sim \alpha^{-1.5}T_R^{-4.5}$. This scaling indicates that a $z$-pinch driven capsule absorbing 1 MJ at 220 eV will have similar stability properties to a capsule absorbing 140 kJ at 300 eV. Work continues on detailed designs of this target concept [19]. Low-cost, 15–20% efficient pulsed power drivers may make this a viable candidate as a fusion energy source, although designing reactor systems with high repetition rates that are based on this technology remains a challenge. Similar arguments suggest that capsules driven by X-rays produced by increased levels of lower intensity green light have similar stability properties as capsules driven by lower levels of 335 nanometer light [20].

As this $z$-pinch example shows, understanding ignition scaling is important in developing practical designs. The work of L&L was based on scaling the behavior of a well tuned implosion to differing implosion velocities and fuel entropies while keeping the drive pressure fixed. Basko and Johner [21] (B&J) performed a similar study, but maintained the implosion Mach number as a fixed quantity. They obtained a different ignition scaling from L&L. Herrmann, Tabak and Lindl [22] obtained the dependence of the ignition energy on implosion velocity, fuel adiabat, and the pressure driving the implosion by simulating thousands of pressure driven implosions:

$$E_{ign}(\mathrm{kJ}) = 50.8\alpha_{in\text{-}flight}^{1.88}(v_{imp}/3\times10^7)^{-5.89} \times (P/100\ \mathrm{Mbar})^{-0.77},$$

where $v_{imp}$ is in cm/s and $\alpha_{in\text{-}flight}$ is the adiabat of the imploding fuel before stagnation. This scaling, in the appropriate limits, agrees with the empirical scalings of L&L and B&J. However, it is quite different from previous theoretically-based ignition models [23] that assume fixed values of hotspot column density ($\rho R$) and ignition temperature ($T$): $E_{ign} \sim \alpha^3_{stag} v^{-10}_{imp}$, where $\alpha_{stag}$ is the adiabat of the fuel after it stagnates. M. Basko [24] claimed that the $\rho RT$ requirement is proportional to $v_{imp}$. This leads to $E_{ign} \sim \alpha^3_{stag} v^{-7}_{imp}$, not in apparent agreement with our empirical scaling. This apparent disagreement occurs because we have implicitly assumed that $\alpha_{stag} = \alpha_{in\text{-}flight}$. In fact, $\alpha$ jumps during the shell stagnation because of preheat by thermonuclear burn products produced in the central region as well as the reflected shock produced in the center that propagates into the imploding shell. The adiabat jump due to the reflected shock is given by $\alpha_{stag} = 0.84 M^{1/2} \alpha_{in\text{-}flight}$ in self-similar models [25] where the ratio of specific heats is 5/3 and $M$ is the Mach number. It is interesting that this same functional dependence on $M$ also describes the stagnation of imploding ICF shells that aren't self-similar and helps to resolve the discrepancy between the empirical ignition formulae and the theoretically derived ones.

Now we have the ingredients to follow Nuckolls' program: we know how to assemble shells symmetrically and stably. We also understand how the stagnated state is formed. But is the approximately isobaric state that we are forming the route to highest gain? An isochoric configuration where the compressed fuel density is uniform and the heated hotspot is out of pressure equilibrium with the bulk of the fuel will lead to adequate gain (gain = 100) at 5–10 times lower driver energy than the conventional isobaric approach. The route to achieving this state is to first compress the fuel then to heat it with an external heating source [26]. Because ignition occurs after the fuel is assembled, it is resistant to quench due to mix. This scheme has come to be known as "Fast Ignition" because the external heating source must be applied quickly. The scheme was enabled by the development of kilojoule class lasers with pulse durations of less than a few tens of picoseconds using a technique called chirped pulse amplification [27]. The high intensity light accelerates electrons to relativistic energies [28]. These electrons then carry the energy to the fuel themselves or via ions which are accelerated by a virtual cathode produced by these electrons as they escape a foil [29]. Variants of the scheme where heating is performed with accelerator driven ion beams [30] or bulk matter have also been suggested [31], although the required power densities have not been demonstrated by these alternate schemes.

Simple models [32] that include hydrodynamic efficiency, stability constraints as discussed above, ignition requirements as defined in simulations [33], ignitor laser coupling efficiency, lead to gain curves as shown in Figure 6. The gain curves shown here assume that the ignitor coupling efficiency is 25% as inferred from recent experiments at ILE, Osaka [34], the compression laser wavelength is 0.33 micrometer, the ignition laser uses 1 micrometer light and the deposition range of relativistic electrons is given by $R(\text{gm/cm}^2) = 0.6T(\text{MeV})$, where $T$ is the temperature of the electron distribution. The hot electron temperature is given by $T(\text{MeV}) = (I(\text{W/cm}^2)/10^{19}\ \text{W/cm}^2)^{0.5}$, where $I$ is the intensity of the short pulse laser with wavelength 1 micron. The gain model optimizes over possible fuel densities and spot sizes. Table 1 shows the sensitivity of the gain curve to the variation of model parameters.

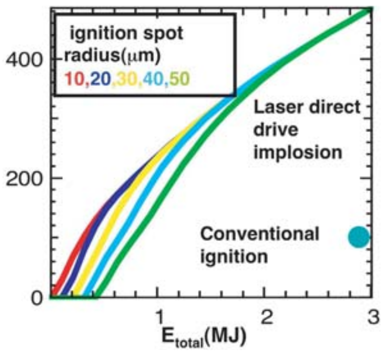
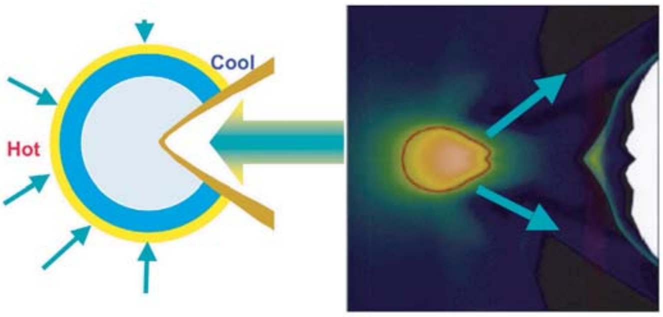


**Fig. 6.** (Color online) Fast ignition gain curves for 5 different minimum ignition spot radii when the fuel compression is directly driven 350 nanometer light.

**Table 1.** Fast ignition gain under various model assumptions.

| Model | Laser energy for gain 100 |
|---|---|
| Nominal model | 0.16 |
| Atzeni ×1/8 | 0.03 |
| Atzeni ×1/2 | 0.05 |
| $\eta_{ign} \times 2$ | 0.075 |
| $\eta_{ign} \times 0.25$ | 1.7 |
| $\eta_{hydro} \times 0.5$ | 0.95 |
| $e^-$ range × 0.5 | 0.09 |
| $e^-$ range × 3 | 0.75 |
| 1 $\mu$m drive | 1.9 |
| 0.5 $\mu$m drive | 0.55 |



(a) (b)

**Fig. 7.** (Color online) (a) Cartoon of cone-focused geometry for Fast Ignition; (b) imploded configuration in cone focus geometry. The compressed fuel assembles without a central low density region because central mass is expelled.

The bulk of the research in Fast Ignition focuses on achieving the nominal model parameters. What are possible areas of research?

1. Implosions need to be designed so that a compact fuel mass is formed efficiently without ejecting the central core as some designs currently do.
2. In the cone focus geometry [35] illustrated in Figure 7, design the implosion so that the fuel assembles near

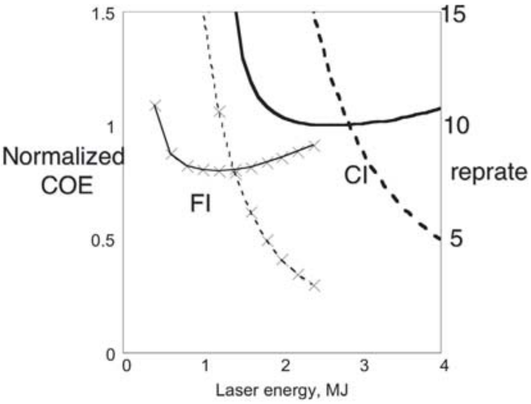


**Fig. 8.** Normalized cost of electricity (COE) and repetition rate for 1 gigawatt electric power plants that use Fast Ignition (FI) or conventional ignition (CI) as a function of driver energy when the fuel is assembled with green light.

the cone tip in order to minimize the distance that energy must travel between the critical surface where the laser light is absorbed and the compressed fuel.

3. Control electron transport so that the energy couples to the fuel.
4. Efficiently produce (>50% from hot electrons in recent simulations [36]) and couple protons to fuel.

What are the consequences of the nominal gain curves for the cost of energy (CoE)? Figure 8 shows [37], for plants producing 1 gigawatt of electricity, the normalized cost of electricity together with the repetition rate for conventional ignition as well as Fast Ignition for fuel compression with green laser light costing \$500/J. The costs optimize near 10 Hz. For larger repetition rates, increased costs arise from additional target fabrication expense as well as the increased recirculating power required to drive the laser. For lower repetition rates the increased driver cost increases the CoE. Fast Ignition provides a major improvement over conventional ignition. For \$2 billion direct capital cost, conventional ignition costs \$2.63/watt of electricity versus \$1.61/watt for fast ignition in specific capital costs [38]. These costs are still much larger than the corresponding specific direct capital costs for fission reactors. The advanced liquid metal reactor (ALMR), a breeder reactor, costs \$1266/kWe at \$1.88B; the advanced light water reactor (ALWR), \$1080/kWe at \$1.4B. Increased fuel cycle costs for fission will reduce the gaps in CoE.

How can we reduce the CoE for fusion? We can increase the unit size. The cost/We is proportional to cost$^{-1/3}$. However, this increases risk for utilities purchasing such plants. Let us speculate how we can increase the gain that can be obtained. There at least are three strategies to accomplish this:

1. Increase the coupling efficiency. Improve focusing of laser to ignition region–grazing incidence cones may deliver 90% of 100 $\mu$ spot to 20 $\mu$. In current experiments, the laser focuses only 20% of its energy to the central spot with the rest distributed over a much larger radius. Figure 9 shows the dependence on the cone opening angle of the fraction of laser energy absorbed in 10 and 50 micron radii for cones terminated with a point or a disk with radius 10 microns. The incident laser beam was focused with $f/7$ into spot with 50 micron FWHM radius. The calculation assumes that the cone is immobile and that the absorption is given by the absorption model of Gibbon [39]. Clearly, a roughened cone surface will degrade the focusing properties of the cone. Quantitative estimates of cone roughening are in progress.
2. Reduce the energy required for ignition below the Atzeni model. Applying the short pulse energy on the surface of the ignition region, implodes the fuel and halves the ignition energy [40]. Tamping the ignition region with a dense, high atomic mass region has a similar effect [41]. Figure 10 shows the results of hydrodynamic/thermonuclear burn calculations of systems where the deuterium-tritium has density 300 g/cm$^3$ and is surrounded by gold with density 1000 g/cm$^3$. For DT radii less than 15 microns and heating durations less than 30 picoseconds, 1 kilojoule deposited in the electrons of the DT results in 1 kilojoule of fusion yield and 5 kilojoules of input energy deposited

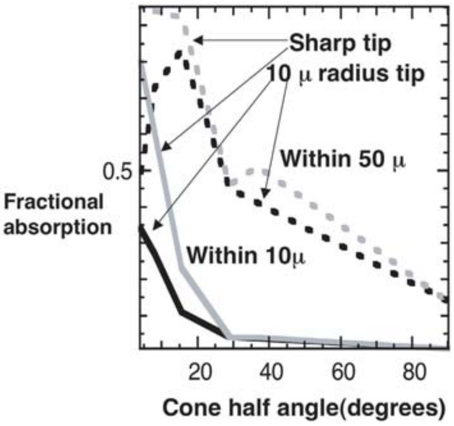


**Fig. 9.** Fractional absorption into 10 and 50 micron radii as a function of cone half-angle for sharp (gray curves) or flat-tipped (black curves) cones.

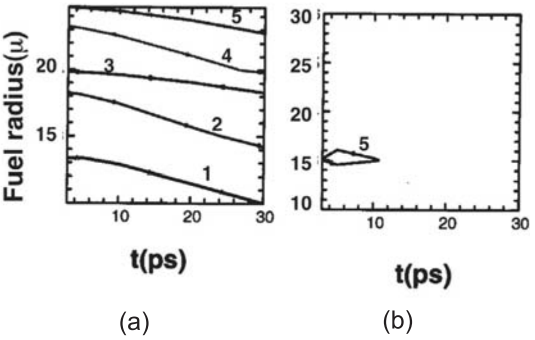


**Fig. 10.** (a) Deposited energy isocontours leading to fusion yield equaling the injected energy for varying fuel radii and energy deposition durations. The curves are labeled by the deposited energy in kilojoules. (b) Same as A except contour labels fusion yield equals 10 times deposited energy.

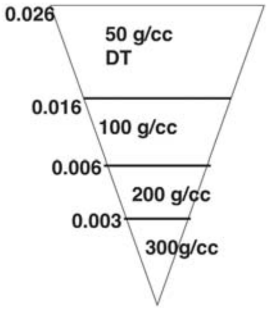


**Fig. 11.** Pie diagram of compressed fuel. Fuel densities in g/cm$^3$ and radii in cm.

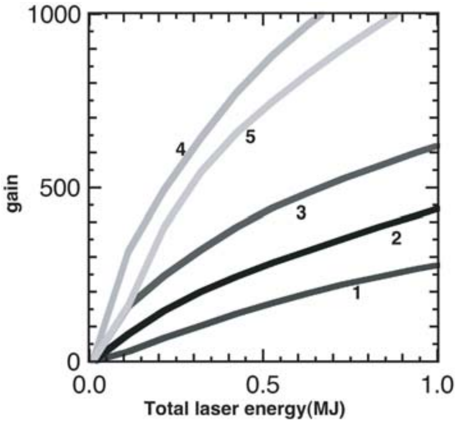


**Fig. 12.** Fast ignition gain curves under a variety of coupling and gain assumptions: (1) nominal assumptions when compression is directly driven 350 nanometer light; (2) set (1) except coupling of ignitor beam to fuel 50%; (3) set (2) except ignition energy requirement 1/3 of Atzeni fits; (4) set (3) except yield doubled because of fuel density gradient; (5) set (4) except fuel compression with green light.

in less than 10 picoseconds yield 50 kJ of fusion yield. When the heated mass is a shell surrounding a sphere of unheated DT with radius 10 microns, 5 kilojoules of injected energy will yield 150 kilojoules of fusion energy as the result strong implosion. These examples can demonstrate low energy ignition and show that thermonuclear runaway can occur for 1/3 the energy required in the Atzeni model. High gain will require coupling this ignited region to a larger fuel mass.

3. Increase the fuel mass for given compression energy by grading the fuel density away from the ignition region. The compressional energy in a mass of DT with density 300 g/cm$^3$ and radius 110 microns is 20.4 kJ. When 20 kJ is supplied to a hotspot, 148 MJ of yield is produced. When the mass is distributed as in Figure 11, the compressional energy is 21.4 kJ, but the yield climbs to 277 MJ.

Applying these three strategies in turn improves the gain curves as shown in Figure 12. The effect of this improvement in gain is to decrease the driver energy required for the CoE optimum from 1.2 MJ to 400 kJ and the fraction of total capital cost due to the laser in Fast Ignition scenarios from 15% to 5.5%.

At this point, the laser cost would not be an important contributor to the CoE. Further improvements in CoE would come from enabling modifications in other parts of the power plant. For instance, the CoE scalings described above come from the an analysis of the Sombrero reactor design [42]. Sombrero is a dry-wall design with a 30 m diameter reactor chamber with the final optics about 30 m from the target in a building 110 m high and 105 m in diameter. Sombrero is designed so that laser beams can be approximately uniformly distributed in a $4\pi$ solid angle as required by direct drive target designs. This design, less laser equipment, costs slightly more than an entire fission plant. Targets that need energy delivered from only one or two directions, would greatly simplify the laser layout as well as enable liquid wall designs like HYLIFE [43] that are more compact and have lifetime first walls. Few-sided illumination would also reduce the containment building size because the final optics and associated neutron beam dumps can be placed near a symmetry axis. This would allow the final optics to be farther from the target for a given $f/\#$ and therefore survive longer. Fast Ignition uses smaller convergence ratios than does conventional ignition and therefore might allow illumination from a restricted set of directions.

We are approaching the end of the beginning of our path to inertial fusion energy (IFE). Thirty-three years after the Nature paper of Nuckolls et al. [4], we are nearing fusion ignition at NIF and LMJ via the indirect drive approach. This will validate physics and demonstrate very complicated laser technology and precise target fabrication. This will be a precursor to fusion energy via ion beams, $z$-pinches and possibly lasers. Direct drive ignition will follow shortly thereafter. The higher coupling efficiency of direct drive will be important for IFE with lasers. Our understanding of Fast Ignition physics continues to evolve along with design ideas. Facilities, like Omega-EP and FIREX, that can approach breakeven (gain $\sim 0.1$) will become available in the next 3–5 years. Achieving high gain in the laboratory will be an outstanding scientific achievement and has required intense efforts by a large number of people. Achieving high gain $10^{10}$ times at low cost and at 10 Hz will require a comparable engineering effort.

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## References

1. G. Gamow, E. Teller, Phys. Rev. **49**, 895 (1936)
2. R.H. Lyddane, R.G. Sachs, E. Teller, Phys. Rev. **59**, 673 (1941)
3. H.A. Jahn, E. Teller, Proc. Roy. Soc. A **161**, 220 (1937)
4. J.H. Nuckolls, A.R. Thiessen, L. Wood, G. Zimmerman, Nature **239**, 5368 (1972)
5. J.D. Lindl, *Inertial confinement fusion: the quest for ignition and high gain using indirect drive* (Springer and AIP, New York, 1997); S.M. Pollaine, J.D. Lindl, Nucl. Fusion **26**, 1719 (1986)

6. Y.B. Zel'dovich, Yu.P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Dover Publications, Mineola, N.Y. 2002), pp. 822–839
7. M. Tabak, "Stability Properties of a Directly Driven Laser Capsule Absorbing 1.7 MJ", Article 2.3.6 in Lawrence Livermore National Laboratory Laser Program 1989–1990, Annual Report, 1995
8. V.N. Goncharov et al., Phys. Plasmas **10**, 1906 (2003)
9. J. Green, RDA internal report, 1980
10. S. Haan, Lawrence Livermore National Laboratory, Livermore, CA, COPD 83–64, 1983 (unpublished)
11. J.W.-K. Mark, Laser Program Annual Report (1984), Lawrence Livermore National Laboratory, CA, UCRL-50021-84, pp. 3–24 to 3–28
12. M. Tabak, Laser Program Annual Report (1986/1987), Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50055-86/87, pp. 2-169 to 2-182 (unpublished)
13. J.D. Lindl, *Inertial confinement fusion: the quest for ignition and high gain using indirect drive* (Springer and AIP, New York, 1997)
14. M. Tabak et al., Nucl. Fusion **38**, 509 (1998)
15. D. Callahan, M. Tabak, Nucl. Fusion **39**, 1547 (1999)
16. J.H. Hammer et al., Phys. Plasmas **6**, 2129 (1999)
17. D. Callahan et al., Plasma Phys. Controll. Fusion **47**, B379 (2005)
18. K. Levedahl, J.D. Lindl, Nucl. Fusion **37**, 165 (1997)
19. M.E. Cuneo et al., Phys. Rev. Lett. **88**, 215004 (2002)
20. L.J. Suter et al., Nucl. Fusion **44**, S140 (2004)
21. M.M. Basko, J. Johner, Nucl. Fusion **38**, 1779 (1998)
22. M.C. Herrmann, M. Tabak, J.D. Lindl, Nucl. Fusion **41**, 99 (2001); M.C. Herrmann, M. Tabak, J.D. Lindl, Phys. Plasmas **8**, 2296 (2001)
23. S. Colgate, A. Petschek, private communication, 1979; J. Meyer-ter-Vehn, Nucl. Fusion **22**, 561 (1982)
24. M. Basko, Nucl. Fusion **35**, 87 (1995)
25. J. Meyer-ter-Vehn, C. Schalk, Z. Naturforsch, **37a**, 955 (1982); A. Kemp, J. Meyer-ter-Vehn, S. Atzeni, Phys. Rev. Lett. **86**, 3336 (2001)
26. M. Tabak et al., Phys. Plasmas **1**, 1624 (1994)
27. D. Strickland, G. Mourou, Opt. Commun. **55**, 447 (1985)
28. S.C. Wilks, W.L. Kruer, M. Tabak, A.B. Langdon, Phys. Rev. Lett. **69**, 1383 (1993)
29. J. Denavit, Phys. Fluids **22**, 1384 (1979); S. Gitomer et al., Phys. Fluids **29**, 2679 (1986)
30. M. Tabak, D. Callahan-Miller, Nucl. Instrum. Meth. A **415**, 75 (1998); A.W. Maschke, Brookhaven National Laboratory report BNL 19008(1974)
31. M. Murakami, "An Innovative Ignition Scheme for IFE—Impact Ignition, "Poster 7/31, *20th IAEA Fusion Energy Conference*, Vilamoura, Portugal, November 6, 2004
32. M. Tabak, D. Callahan, Nucl. Instrum. Meth. A **544**, 48 (2005); M. Tabak et al., Fusion Science and Technology **49**, 254 (2006)
33. S. Atzeni, Phys. Plasmas **6**, 3316 (1999)
34. R. Kodama et al., Nature **418**, 933 (2002); R. Kodama et al., Nature **412**, 798 (2001)
35. S.P. Hatchett, M. Tabak, "Cone focus geometry for Fast Ignition", presentation given at *30th Annual Anomalous Absorption Conference Ocean City*, MD (April 2000); S. Hatchett, R. Stephens, R. Turner, M. Tabak, "New Developments in Design of Cone-Focused Fast Ignition Targets", *31st Annual Anomalous Absorption Conference*, June 3–8, 2001, Sedona, Arizona
36. M. Foord, private communication, 2005
37. W.R. Meier, W.J. Hogan, Y. Kozaki, Fusion Science and Technology **49**, 532 (2006)
38. W.R. Meier, private communication, 2004
39. P. Gibbon, Phys. Rev. Lett. **73**, 0031 (1994)
40. M. Herrmann, S. Hatchett, M. Tabak, Bull. Amer. Phys. Soc. **46**, 106 (2001)
41. J.H. Nuckolls, private communication (2005)
42. W.R. Meier, C.W. von Rosenberg Jr, Fusion Technol. **121**, 1552 (1992)
43. R.W. Moir, Fusion Technol. **26**, 1169 (1994).