The Case for Fast Ignition as an IFE Concept Exploration Program

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Abstract

The fast ignition (FI) concept is a variant of inertial fusion in which the compression and ignition steps are separated. Calculations suggest this would allow a substantial improvement in target gain, and could form the basis of a very attractive power plant. Transporting the energy to ignite a target involves the physics of light-driven relativistic plasmas; a subject which is not well understood. A concept exploration effort to understand the energy transport physics, and also to clarify the merits of a FI IFE power plant could justify a proof-of-principle program on the National Ignition Facility.

1. Introduction

The ICF program has focused its attention on "central hot spot" ignition, whereby a hollow spherical shell of DT ice containing DT gas is compressed, creating a central hot spot surrounded by a dense shell of cold DT [1]. The alpha particles from fusion in the hot ignition spark create a propagating fusion burn in the cold fuel. The requirements for low mode spherical symmetry and for high mode uniformity of the target and drive are stringent in this scheme; the former because a large spherical convergence ratio is needed to produce the ignition spark and the latter because the required high drive pressure leads to large Rayleigh-Taylor instability growth of high mode number perturbations of the imploding shell. The target gain that can be achieved is limited by the high investment of energy in compression of the fuel and the threshold energy for ignition is high because the spark density is much lower than the fuel density in isobaric ignition. These factors set the minimum size of the driver and push the energy input for high gain to a few megajoules. Gain values are higher for direct drive than for indirect drive due to coupling efficiency differences, but it appears difficult to obtain gains greater than 100, and values of a few tens are more conservative. While there are several drivers that promise high enough efficiency for the driver efficiency-target gain product to lead to an acceptable commercial inertial fusion energy (IFE) power plant, and while this is consistent with the ~GW_e size of power plants, it would be attractive to have an inertial fusion concept with a higher efficiency-gain product and allow a smaller driver size.

The Fast Ignitor (FI) may be that concept [2]. With FI the compression and ignition steps are separated. A target of DT is compressed to high density at low temperature by lasers or particle beams. A second, very high intensity beam delivers the energy used to ignite the compressed core and heats an ignition spark at the density of the cold fuel in isochoric ignition (Fig. 1). The FI concept promises much higher gain for the same driver energy than isobaric hot spot ignition, as shown in Fig. 2. In addition, the "ignition threshold" that occurs at about 1 MJ for hot spot ignition may be reduced to ~100 kJ [3]. These changes in the drive requirements for inertial fusion give rise to a cascading sequence of changes to the concept for inertial fusion energy that may lead to a much more attractive inertial fusion power plant (as discussed in the next section) with a much easier development pathway.

Fast Ignition must however resolve physics problems in an unexplored regime in order to justify advancement to the next, proof-of-principle, stage. Success in demonstrating efficient transport of a high energy pulse into a dense plasma, development of a target design for the compression phase and definition of a power plant concept would justify adapting NIF for full scale proof-of-principle experiments.

The most critical issues involve understanding the physics of energy transport between the ignitor laser beam and the ignition spark. The photon pulse has to deliver up to 50 kilojoules of energy in ~10 picoseconds in a spot a few 10s of microns across located in the dense fuel. The intensities involved accelerate electrons to relativistic energies and lead to relativistic self-focussing of the laser beam, and the time involved is sufficient for the plasma structure and laser beam to co-evolve; there is much novel physics in this regime. The targeted ignition spot has a density much higher than the (relativistically corrected) critical density for transmission of light, and the energy of the laser is converted near that critical density surface to a directed jet of high energy electrons. The resulting electron currents greatly exceed the Alfven limit and require return current cancellation. The resulting EM fields modify the global electron flow, which is also subject to small scale Weibel instability. All of these phenomena have to be understood in some detail for success in fast ignition.

A Fast Ignition research program, carried out at the innovative concept exploration level, is proposed in Section 4. There we describe the experimental and theoretical program required. Basically, both our experimental and theoretical understanding must be upgraded before we can achieve our goal.

Fast Ignition research will have spinoffs to and connections with other research areas. The high light intensities and plasma densities are relevant to laboratory astrophysics, and can create powerful x-ray and nuclear particle sources, which may have other applications.

2. Apparent FI IFE advantage

2.1. Higher Gain Targets

Fast Ignition ignites an isochoric (uniform density) target vs the isobaric (uniform pressure) target used for central hot spot ignition [3] (Fig. 1). There are fairly well established requirements for the ignition spark. Isochoric ignition needs about 35 kJ to ignite a 30 μm radius spot in a 200 g/cc target. Reasonable assumptions on transport efficiency suggest ~100 kJ, 10 ps laser pulse would be required to deliver this energy. [4]

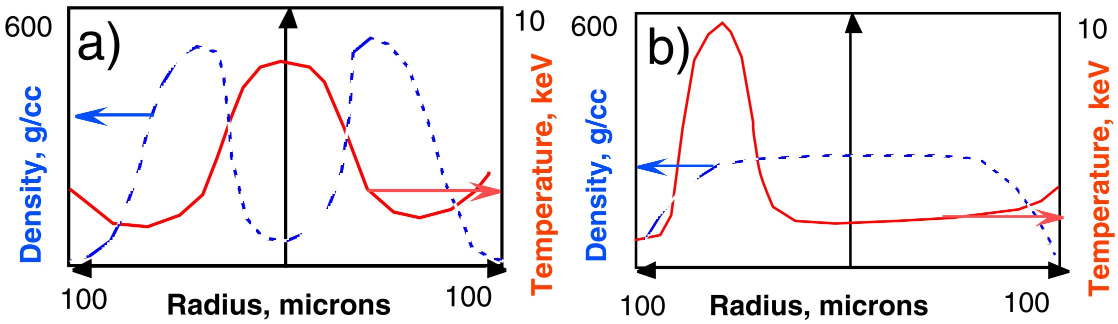

Figure 1: Density (blue, dashed) and Temperature (red, solid) for an IFE target at ignition for a) the isobaric target used in conventional central hot spot ignition, and b) for the isochoric target used in fast ignition.

The required ignition energy is independent of target size. The ignition threshold corresponds to a target size equal to the ignition spark size. Larger targets require proportionally more compression energy, but no more ignition energy, so the gain increases dramatically until the compression energy dominates. Computed gain curves [4] are shown in Fig. 2, which also gives the comparison with direct and indirect isobaric central ignition. For a 1 MJ input energy (90% going to compression) the target gain can be ~300.

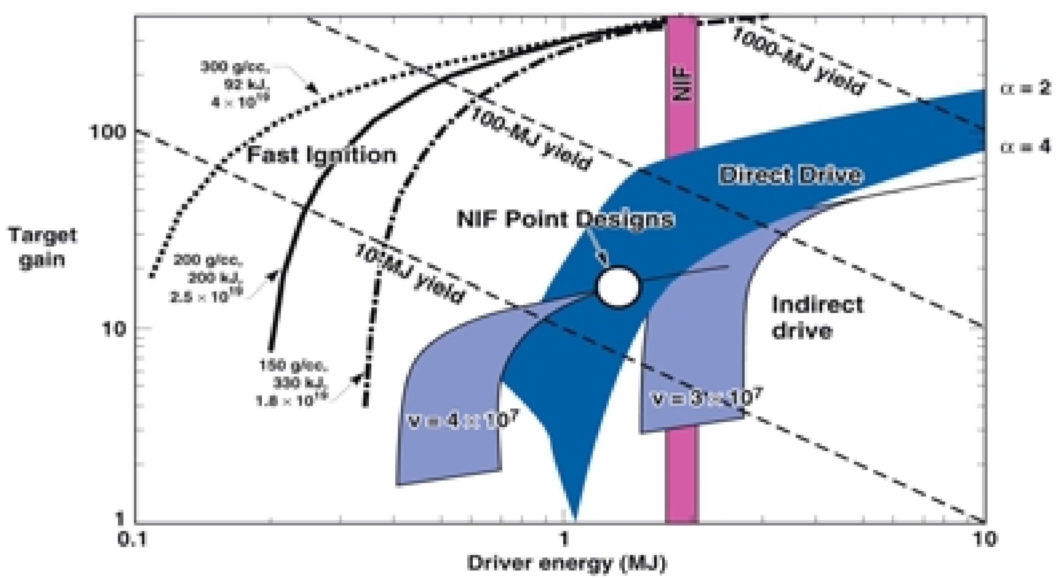

Figure 2: Target gain versus laser driver energy. Isobaric central spark indirect drive (including the NIF point design) and direct drive are shown for comparison with fast ignition gain for fuel densities 150, 200 and 300 g/cc. Labels indicate fast ignitor laser pulse energy and intensity$\times$(wavelength)^2 see [4] for further details.

2.2. Benefits of Higher Gain for IFE Power Plants

The increased gain described in the previous section has substantial consequences for plant design and economics. Figure 3 is an energy flow diagram for an IFE power plant showing key design parameters as described in the figure caption. One of the obvious benefits of the FI target is the higher target gain, G, since the recirculating power needed to operate the laser is inversely proportional to G. This results in a smaller and lower cost power plant for a given net output power. An even more important impact is that the higher gain is achieved with a smaller and less expensive laser.

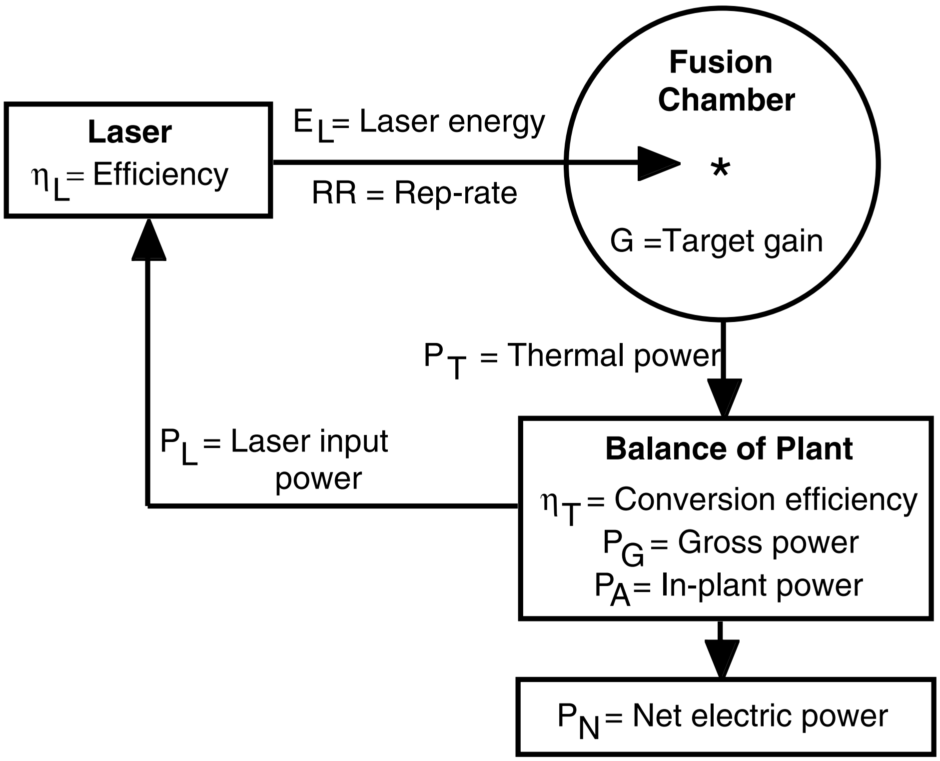

Figure 3: Flow diagram for a laser fusion power plant. Fusion targets are ignited at a pulse repetition rate, RR, at the center of the fusion chamber. The resulting thermal power, P_T, is converted to electricity with an efficiency of η_T. Part of the gross electric power, P_G, is used for in-plant or auxiliary power, P_A, part is recirculated to operate the laser, P_L, and the remainder is the net power available for sale, P_N. The laser power is given by $P_L = (E_L \times RR)/\eta_L$, where E_L is the energy of all the laser beams, the RR is the laser rep-rate, and η_L is the laser efficiency.

To illustrate the impact quantitatively, we consider two representative examples, one using conventional central hot spot ignition targets and the other using fast ignitor targets. While we have not completed conceptual design studies for IFE plants using fast ignition and thus have not addressed all the important interface issues, the comparison at least gives an indication of the potential advantages of using FI. Table 1 compares design parameters for the two cases. We start with the target gain for a given laser energy. The hot spot targets require a laser energy of 4 MJ for a gain of 100, and the fast ignitor achieves a gain of 300 with a 1.33 MJ laser, so both cases have a target yield of 400 MJ per shot. The G = 100 at E = 4 MJ performance is midway between the direct drive gain curve used in the Sombrero study [6] and the indirect drive baseline used in Ref. 5. The G=300 at E= 1.33 MJ is taken from the calculated curve shown in Figure 2 and Ref. 4. (For the purposes of this exercise, it is not critical that these gains are exact or that the chosen design points are optimal for the particular cases.) The power plant parameters in Table 1 are based on the HYLIFE-II liquid wall design [9] with a net plant output of 1000 MWe. Note that the higher gain of the FI allows a lower pulse repetition rate (5.48 vs. 6.65 Hz), smaller gross electric power (1131 vs. 1355 MWe), and much smaller recirculating power requirement for the laser (81 vs. 295 MWe).

Table 1. Comparison of Plant Parameters: Fast Ignition vs. Hot Spot Ignition.

	Fast Ignitor	**Hot Spot**
Laser energy, MJ	1.33	4
Laser efficiency, %	9	9
Target gain	300	100
Target yield, MJ	400	400
Repetition rate, Hz	5.48	6.65
Thermal power, MW	2632	3151
Power conversion efficiency, %	43	43
Gross electric power, MWe	1131	1355
Auxiliary power, MWe	50	60
Laser power, MWe	81	295
Net electric power, MWe	1000	1000

The impact on the economics of the IFE power plant are significant. Since the cost of electricity is essentially proportional to the plant total capital cost, we use this metric for the comparison. However, if indirect drive can be used, thick liquid walls become a possibility with their potential of further lowering of the cost of electricity. Figure 4 compares the relative capital cost of the two cases normalized to the plant using the central hot spot ignition target. As indicated, the capital cost with the FI is ~ 37% less than with a hot spot ignition target. In this example, the laser cost is based on the DPSSL driver study [7] and scales linearly with laser energy. In addition to the significant reduction in the laser cost, there is a smaller reduction in the reactor plant equipment (RPE) and balance of plant (BOP) costs due to the smaller plant power with the FI. For the hot spot ignition target, the cost fractions are: Laser (49%), BOP (26%), and RPE (25%). With the FI target the fractions are: Laser (29%), BOP (36%), and RPE (35%). The FI case includes an allowance of $50M (direct cost) for the ignitor laser.

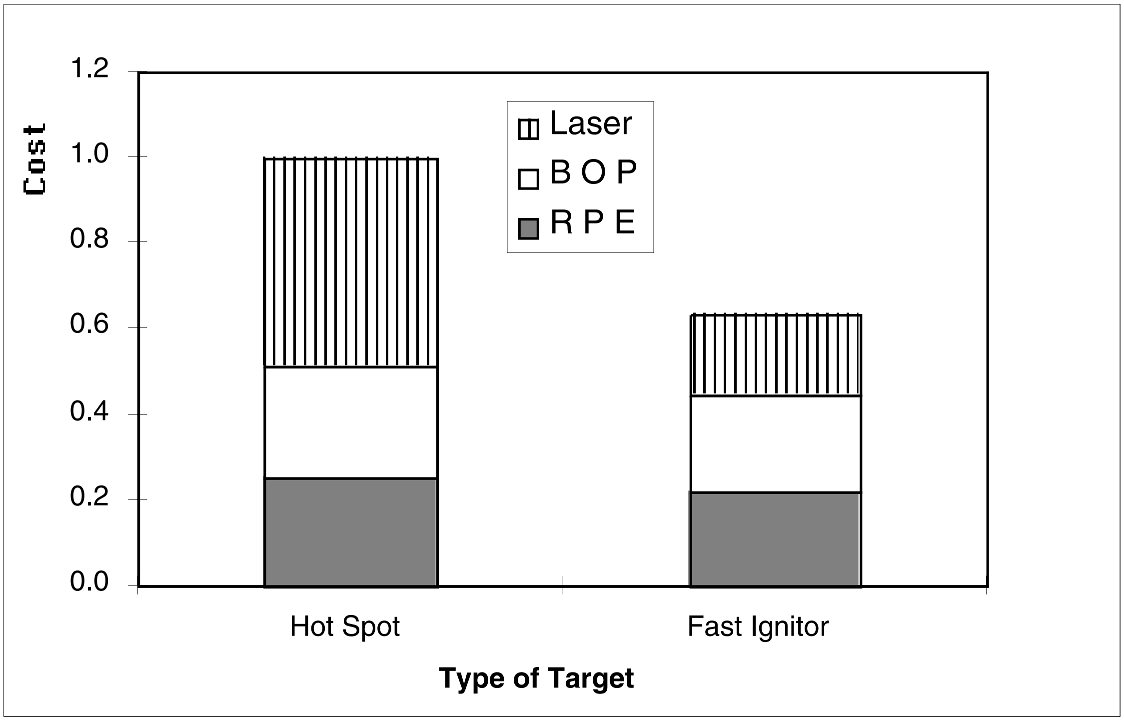

Figure 4: This chart compares the breakdown of capital costs for two 1000 MWe IFE power plants: one using conventional hot spot ignition targets and the other using fast ignitor targets (see Table 1 for comparison of parameters). Using the fast ignitor significantly reduces the cost of the laser (by ~60% for the DPSSL assumed here) and reduces the total capital cost of the plant by 37%. The higher gain with the fast ignitor results in a smaller recirculating power requirement for the laser and thus a smaller gross electric power, which translates into lower costs for the reactor plant equipment (RPE) and balance of plant (BOP).

2.3 Possible simpler, more rugged targets

Fast Ignition requires a target with pure DT in the surface igniting volume, and a well connected isochoric fuel mass. The density and pressure are less than in central hot spot ignition and therefore in principle easier to achieve, allowing some relaxation of hydrodynamic stability constraints on high mode driver uniformity and low mode capsule spherical symmetry. The bulk of the fuel does not have strict requirements for composition (it could be tritium lean, for instance), or for shape. (It should be in a roughly spherical form but irregularities are tolerable.) [8] Since a central spark is not needed, there is no problem with central mixing caused by a rough interior ice surface. (In fact one might encourage mixing to keep any central gas cool.) Given sufficiently relaxed ice roughness criteria, one might freeze a layered target to 4 K, increasing the DT ice strength and reducing temperature control requirements, to ease storage and injection of targets.

If enough ignitor energy is available, fuels with substantially reduced cryogenic requirements become possible. For instance $B_2D_3T_3$ melts above liquid nitrogen temperatures. It may also be possible to design gas phase DT + impurity capsules which radiatively cool to reach high density. The high intensity beam would then ignite the mixture of fuel plus impurity.

2.4 Lower energy, more flexibly placed drivers

Relaxation of sphericity requirements, as discussed in the previous section, gives scope for creative target designs and attractive driver beam configurations. It might allow driving the implosion inside a hohlraum with a cluster of drivers and ignitors at opposite axes (Figure 5). This permits a very attractive reactor chamber design (following section).

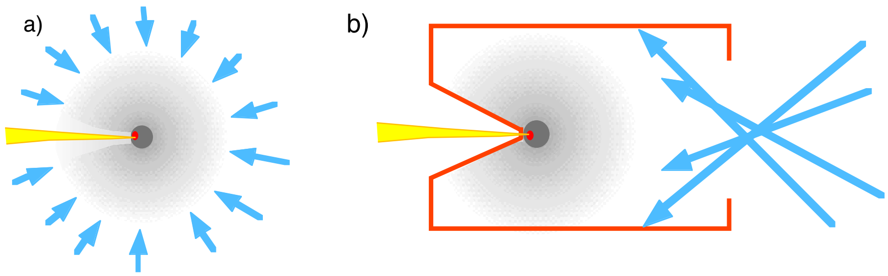

Figure 5: FI IFE target concepts showing driver (blue) and ignitor (yellow) illumination geometries for a) direct drive symmetrically illuminated and b) indirect drive, illuminated from one end. In a) the ignition laser has to penetrate an overlying plasma haze before heating the target. In b) using cone focusing, the plasma blowoff is excluded from the ignitor laser path and the driver lasers can be concentrated at one end of the chamber.

By decoupling the implosion from the ignition we are free to use lasers, ion beams or even Z-pinches to drive the implosion while the chirped-pulse laser is reserved for ignition. The design of the target and drive for fuel compression design will minimize the length and mass per unit area of coronal plasma the ignitor beam must traverse and, therefore, reduce the energy transport problem.

2.5 Power Plant Design

If the target can be designed to be illuminated from two sides within modest cones, as discussed above, then the thick liquid wall protection concept called HYLIFE-II can be employed. [9] The combination of higher gain targets and longer-lived chamber structures in the HYLIFE-II concept [10] results in a substantial reduction in the calculated cost of electricity. (For a mature series of plants from ~6¢/kWh for direct drive to ~4.2¢/kWh for FI at 1 GW_e and from ~4.5¢/kWh to ~3.3¢/kWh at 2 GW_e size.) It also virtually eliminates, or greatly reduces, the need for an expensive 14 MeV neutron source to do structural materials development.

3. Major FI IFE questions

Energy transport is the key area of physics uncertainty

The most challenging problem in fast ignition is to transport energy efficiently from ignitor laser beams to the ignition spark. This entails delivery of up to 50 kJ of energy in 10 to 20 ps into a spark of diameter less than 50 μm. The laser light must penetrate sub-critical density plasma surrounding the compressed fuel and be converted efficiently to relativistic electrons near the critical surface. These electrons must penetrate additional super-critical density fuel and deposit their energy in the spark volume. Hydrodynamic design can minimize this path by reducing both the mass per unit area and distance separating the critical density and the ignition spark. Nevertheless energy transport in both sub-critical (transparent) and super-critical (opaque) plasmas are relatively unexplored regimes where the physics is new and outcomes cannot be confidently predicted on the basis of current modeling capability or experimental data. Concept exploration study of these issues is essential before fast ignition could be ready for a proof of principle test

3.1. Advantages suggested by 0-d models need realistic modeling

A small set of 1-D direct drive calculations has been performed in rough agreement with the 0-D results for convergence ratio and in-flight-aspect-ratio. There have been preliminary hole-boring calculations through millimeters of overdense plasma based on these 1-D calculations. So the calculations to date have shown no show-stoppers.

They do not however, adequately address the problem. We need to extend the suite of 1-D capsule designs. We also need to extend these hole-boring calculations including the effects of plasma instabilities, diffraction, 3-D effects and magnetic field generation. There have been no integrated calculations utilizing indirect drive for Fast Ignition along the lines of Figure 5b.

3.2. Penetration of coronal plasma is complex – is there a better way

Even if it is possible to hole-bore through millimeters of plasma as in the design of Figure 5a, the operation may consume a significant amount of chirped laser energy. Two designs worth exploring are an aspherical variant of Figure 5a, where the radius of curvature of the implosion capsule where the ignition beam will enter is much smaller than that at the antipode, and the design of Figure 5b.

3.3 Physics of high intensity beam interacting with plasmas is complex

The intensity$\times$(wavelength)^2 needed to generate the ~1 MeV electrons is ~10^{19} Wμm^2/cm^3. At that intensity, the pulse can substantially redistribute electrons in its path. Since the plasma has substantial refractive index, both pulse and plasma structure can co-evolve. The beam can filament or focus. The relevant physics here include relativistic self-focusing as well as thermal and ponderomotive filamentation. In addition, the large self-generated magnetic fields in this coronal region will affect electron transport and optical guiding mentioned above. In this region, collective or free-wave acceleration mechanisms may produce a very small minority population of electrons with energies far above 1 MeV.

The MeV electrons are primarily generated at the critical density surface. The forward current is ~ 1 Giga-Ampere and exceeds the Alfven limit by a factor of several thousand necessitating almost complete current compensation by cold return current. Weibel instability and global magnetic guiding of the electron flow are predicted. All these phenomena must be understood better, and our modeling ability improved, to the point that we have a fully quantitative modeling capability for energy transport under ignition conditions.

4. Outline of a concept exploration program

An experimental program is needed to address the uncertain physics of energy transport by laser radiation at sub-critical density and by electrons at super-critical density. Experiments should be at relevant pulse length and intensity and in preformed plasmas similar to the plasma to be penetrated in a fast ignition target. The goal would be demonstration of efficient energy transport to a spark sized region in compressed matter. The principle type of laser facility needed is a petawatt (PW) power multi-kilojoule energy ignitor beam synchronous with one (or better two) beams of kilojoule energy and nanosecond pulse duration giving pre-pulse plasma forming capability. The LLNL Spire and GA RPLF proposals describe suitable lasers. A similar capability may also be an early option at NIF. Smaller high intensity lasers in university scale facilities can also contribute significantly to the basic science.

The above experiments should be closely linked to development of improved 3-D modeling capability for laser propagation in plasma at relativistic intensities. This should include PIC modeling and more global scale propagation modeling. 3-D PIC is also suitable for modeling absorption, hole boring, and initial stages of electron energy transport. More global electron energy transport modeling requires hybrid fluid/PIC codes.

A modeling program using existing hydrodynamic codes is required to establish an optimized FI target design. That work would establish the baseline for proof-of-principle experiments.

The modeling program would also begin to define target and driver requirements. This information is needed to develop a description of the basic features and advantages of a FI-IFE power plant and would establish the justification for pursuing the Fast Ignition concept to the proof-of-principle level.

5. Acknowledgements

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