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Abstract

Fast ignition is an alternate concept in inertial confinement fusion, which has the potential for easier ignition and greater energy multiplication. If realized it could improve the prospects for inertial fusion energy. It poses stimulating challenges in science and technology and the research is approaching a key stage in which the feasibility of fast ignition will be determined. This review covers the concepts, the state of the science and technology, the near term prospects and the challenges and risks involved in demonstrating high gain fast ignition.

I. Overview

In inertial confinement fusion (ICF) research, fast ignition (FI) has the potential for higher gain, lower ignition threshold and less stringent implosion symmetry requirements than central hot spot (CHS) ignition. Research worldwide is approaching a critical stage where conclusions on the feasibility of FI should be obtained. The challenges span laser science and technology, plasma numerical modeling and design, novel diagnostics and novel science of energy transport and heating by extremely high current densities of MeV electrons and protons. New short pulse high energy lasers are being developed through innovations such as optical parametric chirped pulse amplification (OPCPA), large area multi layer dielectric (MLD) gratings, large aperture pulse compressors with tiled MLD gratings and uni-phase operation and focusing of multiple short pulse beams. Numerical modeling is being pushed to new extremes in multi-scale physics. Models are combining the intense short pulse laser plasma interaction treated by explicit particle in cell (PIC) methods, the transport of energy by electrons and protons treated by implicit hybrid PIC methods and radiation-hydrodynamic modeling of implosion and compression. Diagnostics of the short pulse interaction phenomena are being developed and intense effort is going into benchmarking numerical models against experimental measurements. The next phase of fast ignition research will be integrated experiments and modeling using new larger scale facilities in the USA and Japan. The results will determine the requirements for full-scale fast ignition which could then be demonstrated by short pulse modification of major ICF ignition facilities or with proposed new dedicated FI facilities. A recent journal special issue on FI is good source of detailed information[1]. In the following sections this review will provide information on questions which include: what is fast ignition? why develop it ? what has been achieved ? what are the near term prospects and remaining challenges ? can high gain fast ignition be demonstrated and with what risks? and, is there a route to fusion energy?

II. Introduction

A. Magnetic and inertial fusion energy

The quest for fusion energy is intensifying with commitment to the 'International Tokomak Experimental Reactor' (ITER), the flagship project in magnetic fusion energy[2] (MFE). ITER is scheduled for initial operation in 2015 and demonstration of burning plasma in 2021. Inertial fusion energy (IFE) offers a radically different path currently pursued less aggressively than MFE, but expected to receive enhanced attention with the anticipated demonstration of ICF ignition at the US 'National Ignition Facility' (NIF)[3] in 2010/11 and at the French 'Laser Mega-Joule' (LMJ)[4] in 2012/13.

MFE uses magnetic confinement of deuterium tritium (DT) plasma at a low density ($\sim 4x10^{-10}gcm^{-3}$) in a toroidal vacuum vessel of 10 m scale. Thermonuclear fusion is at a slow rate with continuous burning and addition of fuel. The energy confinement time is about 10 s and is determined by turbulence dominated particle transport across the magnetic field. The ratio of fusion power to injected power is called the Q of the process. There is a large net output of fusion power ($Q>>1$), though the reaction stops if energy input is stopped. ITER is designed to generate 0.5 GW of DT fusion power at $Q=10$ in 1000s periods of repetition frequency and number limited by nuclear activation of the facility.

By contrast ICF is the thermonuclear explosion of a very small DT plasma (~100 micron diameter) adiabatically compressed to 300 to 1000 gcm^{-3} at close to the minimum internal energy, the Fermi energy. It is ignited in a hot spot containing only a few percent of the mass and a thermonuclear burn wave then consumes the main fuel mass. Energy is confined only for the time it takes for explosive decompression, which is about 10^{-10} s. The ratio of fusion burn energy to input energy from the driver used to compress and ignite the plasma, is called the gain. In conceptual IFE the fusion energy is typically ~100MJ with 100x gain. A power output of ~1GW would be achieved by repeating the process at a rate of 10 explosions per second. NIF should produce 10 to 100MJ of fusion energy using 1 to 1.8MJ of laser energy. NIF ignition events will be single shot with numbers limited by nuclear activation of the target chamber and other laser operational factors.

B. Principles of ICF and FI

Compression in ICF is obtained through the implosion of an ultra-smooth hollow spherical shell of ~2 mm diameter comprised of an outer layer of Be, C or polymer with a ~ 0.1 mm thick DT ice layer on its inner surface. The outer surface of the ablator is intensely irradiated either by laser radiation (direct drive)[5] or by thermal soft x-rays in a hohlraum (indirect drive)[6] as illustrated in figure 1. The hohlraum is a canister of Au and other high Z materials with laser entrance holes at each end and it encloses the spherical capsule. Its interior walls are heated to a temperature of ~3×10^{6} K by intense laser radiation so that they emit Planckian radiation with intensity peaking in the soft-x-ray region of the spectrum. In both direct and indirect drive, intense irradiation of the ablator burns away the surface and the rocket-like reaction pressure from the ablated plasma implodes the capsule to ~1/30 of its initial diameter. The radiation intensity is ~ 10^{15} Wcm^{-2} , the ablation pressure is ~1.5×10^{8} bar and the capsule implodes in ~ 5×10^{-9} sec with a maximum velocity of ~ $3.5\times10^{7} cms^{-1}$. The driver energy is 1 to 2 MJ. Indirect drive couples only < 15 % of the laser energy to ablation of the capsule compared to ~ 50% for direct drive. Direct drive has lower ablation pressure but is overall about 2x more efficient than indirect drive in converting laser energy to internal energy of the compressed fuel.

There are two methods of ignition used with either type of drive as illustrated in figure 2. The most developed is CHS ignition. It relies on the implosion alone to produce ignition. Sudden increases in the ablation pressure resulting from temporal shaping of the laser pulse, launch typically four successive shock waves in to the DT which compress it almost adiabatically to ~1000 gcm^{-3} and a temperature kT ~ 0.5 keV. The hollow center of the shell is filled with DT gas, which undergoes more volumetric compression and adiabatic heating. In addition the shock waves converging at the center create further shock heating of the central hot spot to reach kT~ 5 keV, the ignition temperature. The imploded plasma at stagnation is isobaric and the hot spot density is an order of magnitude lower than the main fuel at ~100gcm^{-3}. The inertial confinement time is proportional to the radius and Lawson's criterion is satisfied by a sufficient density radius product ρr. More precisely the fusion burn efficiency is given by $\rho r/(\rho r+7gcm^{-2})$. In full scale CHS ICF the main fuel has ρr ~3gcm^{-2} to give 30% efficient thermonuclear burn and the compressed fuel layer is ~ 30 μm thick. The ignition hot spot has ρr ~ 0.3 gcm^{-2} (radius ~ 30 μm) in order to reabsorb the alpha particles from D-T thermonuclear fusion and thus launch a thermonuclear burn wave. Its thermal energy content scales as $1/\rho^2$, or equivalently as $1/P^2$ where P is the pressure. Lower ignition threshold therefore requires higher pressure. Since the Fermi energy scales as $\rho^{2/3}$ more energy is invested in compressing the fuel to higher pressure and density and the thermonuclear gain is reduced. CHS ignition minimizes the driver energy needed for ignition by using the highest possible pressure but that threshold is not less than 1 to 2MJ.

Fast ignition (FI) takes advantage of these scaling considerations by igniting a small region in the main fuel mass at the same density as shown in figure 2. This ignition is isochoric. The energy input to the hot spot is from an intense short pulse of electrons (or protons) generated by ultra- intense laser radiation. The FI hot spot density can be less than for the CHS when the fuel density is also less (e.g. both at ~ 300 gcm^{-3}). As a result the gain can be higher and the ignition threshold lower. The fast ignition pulse duration must be less than the inertial confinement time governed by the radius of the hot spot, which is 20ps for a density of 300 gcm^{-3}.

When FI was first proposed[7,8] it was envisaged as shown in figure 3, that a powerful precursor laser pulse of about 10^{-10} s duration would expel plasma radially by its light pressure gradient (the ponderomotive force) and create a channel up to the critical density $N_c \sim 3x10^{-3}$ gcm^{-3} $/(\lambda/1\mu m)^2$ electrons cm^{-3} at which the laser is reflected. It would then hole bore by axial light pressure pushing the critical density closer to the dense fuel, all this through the 1 mm scale length of the peripheral plasma of an implosion. A following main pulse would be focused into the channel. At the critical density most of the laser power would be absorbed launching forward directed electrons of average energy ~1MeV. The range of a 1MeV electron in the DT fuel would match the ρr of the ignition hot spot. The average energy of the electrons is related to the ponderomotive potential or oscillatory energy in the light wave. At relativistic intensities the electrons execute a forward directed zigzag motion due to the dominance of the Lorentz force from the EM field. At the critical density they are projected forward into the denser plasma. Their energy scales as $(I\lambda^2)^{1/2}$ and at $\sim 5x10^{19} Wcm^{-2}$ μm^2 it is at the required 1MeV.

Early research on laser induced plasma channel formation and propagation of powerful pulses in channels showed that there were many complications and motivated an alternative design using a hollow Au cone inserted in the spherical shell as illustrated in figure 4. Implosion around the cone produces compressed plasma at the tip of the cone. The hollow cone allows the short pulse laser to be focused inside it and to generate hot electrons at its tip very close to the dense plasma. No channel formation in the plasma is required. Seminal experiments with this method are described later.

A variant cone concept also illustrated un figure 4 uses a thin foil to generate a proton plasma jet with multi MeV proton energies Hot electrons exert a large pressure which drives rapid expansion of a proton plasma from the rear foil surface coated with proton rich matter. The flow is perpendicular to the rear surface and spherical curvature focuses the proton plasma jet. In this concept the protons deliver the energy to the ignition hot spot.

III. The advantages of fast ignition

The high gain and low threshold advantages of FI are illustrated in figure 5 relative to gains anticipated in ignition target designs for the NIF using CHS ignition by either direct or indirect drive[9]. These estimates for FI assume direct drive with 8% hydrodynamic efficiency. The possibility of 300x gain with full scale targets having a fuel $\rho r \sim 3 gcm^{-2}$ and 100 x gain at half scale with $\rho r \sim 1.5\ gcm^{-2}$ is highlighted. An additional advantage is the relative immunity of FI to failure due to hydrodynamic instability. Perturbation growth on the outer and inner surfaces of an imploding shell illustrated in figure 6, due the Rayleigh Taylor instability, occurs at the outer surface where lower density ablating plasma accelerates the higher density imploding shell and at the inner surface when lower density hot gas decelerates the incoming dense shell in the stagnation phase. The shell can break up before the implosion is complete or fingers of cool dense fuel can penetrate the CHS quenching ignition. The instability growth exponent scales in proportion to the multiplication of the drive pressure by the implosion. Since the fuel in FI is at lower pressure than in CHS ignition, there is consequently less instability growth for the same ablation pressure. The only requirement in FI is to avoid break up of the imploding shell, quenching of the CHS being of no consequence. FI is therefore less sensitive to instability growth and can have less instability growth, both of which ease requirements on the smoothness of the target surfaces and the uniformity of the drive.

IV. Progress in FI Science

Progress in the science of FI has been rapid as a result of intensive research worldwide.

A. Ignition conditions

Numerical radiation-hydrodynamic models have been used to describe the ignition process assuming either heat input or more accurately that electron or ion beams irradiate the hot spot [10]. The work has established the FI ignition conditions relative to those for isobaric (CHS) ignition, as kT=10 keV and 5 keV and ρr= 0.5 and 0.3 gcm^{-2} respectively. The higher requirements at the same density for FI are due to the energy lost to a blast wave generated around the hot spot because it is at much higher pressure than the cool fuel (isochoric) in contrast to the isobaric CHS. Power law fits to the numerical data have given useful scaling laws for the hot spot parameters, for example the hot spot energy requirement $E/1kJ = 140(\rho/100gcm^{-3})^{-1.8}$. Modeling specific to proton ignition has also been carried out [11]and adds consideration of transit time spread, and optimum proton energies in the plasma jet.

A compressed density of 300gcm^{-3} has been widely recognized as an upper limit because hot spot diameter scales as 1/ρ and the <34 μm requirement is seen as a lower limit. It is impractical to deliver electron or proton energy to a smaller spot. The scaling of the beam intensity in proportion to ρ imposes another upper limit on the density. The hot spot energy is then 20 kJ and the pulse duration must be <20ps setting intensity at $\sim 7\times10^{19}$ wcm^{-2}. The electron current for 1 MeV electrons is 1GA. The intensity is already at a level at which a laser of 1μm wavelength would generate ~ 1MeV electrons. The laser intensity must however be higher than the electron beam intensity, the multiplier being at least the inverse coupling efficiency between laser energy and thermal energy in the hot spot. Coupling efficiency as discussed later, is not expected to exceed 20% so unless there are other mitigating factors, there will be a need to use the $(I\lambda^2)^{0.5}$ scaling to reduce the electron energy by reducing the laser wavelength below 1μm. The second and third harmonics of the 1.05μm Nd glass laser are being considered in this context.

B. Cone guided implosions

The cone guided implosion concept was first developed by hydrodynamic modeling[12] as illustrated in figure 7. It gave a major boost to interest in fast ignition through seminal experiments at the Gekko laser facility in Japan[13] illustrated in figure 8. The implosion laser delivered 1.5kJ in 1ns at 0.53 μm wavelength in 9 beams to implode a CD shell of 350 μm diameter and 6 μm thickness around a hollow 30^o Au cone with its 10 μm thick, 20 μm wide tip located 50 μm from the center of the sphere. The compressed plasma formed a 50 μm diameter blob at 50 gcm^{-3} located 50 μm from the cone tip. When a 300J, 600ps, 0.5 PW laser pulse of 1.05 mm wavelength was focused inside the cone tip at the instant of maximum compression, there was a 1000x enhancement of D-D fusion neutron emission which indicated 20% coupling of ignitor laser energy to the implosion. The dramatic impact of this result is emphasized when it is compared with the coupling efficiency to the hot spot in indirect drive CHS ignition which is ~1%.

The experiments at Gekko leave a major question for current research which is whether the 20% efficiency can be obtained in full scale FI. The spatial scale at Gekko relative to a full scale 3gcm^{-2} implosion was ~1/4, with the compressed plasma being approximately the same size as the FI ignition hot spot and subtending a solid angle ~1sterad seen from the tip of the cone. At 4x the scale and with self similarity of the hydrodynamics, the solid angle would be reduced to 1/16 sterad. The 50 gcm^{-3} of the implosions at Gekko is also well below the 300gcm^{-3} density envisaged for FI, further complicating understanding of the scaling.

The study of the hydrodynamics of cone- guided implosions has advanced considerably since the initial work. Designs have been developed for the larger Omega implosion facility in the USA which has 60 beams delivering 25 kJ at 0.35 μm wavelength[14]. Both indirect[15] and direct drive[16] of cone -guided implosion of CD shells has been successfully tested and compared with modeling at Omega as illustrated in figure 9. Other experiments at Omega have measured the time of shock break through into the cone by streaked optical pyrometry [17].

Implosions producing FI required density with a minimal central hot spot, have been designed through 1D modeling and the development of implosion scaling laws[18]. The final pressure in an implosion scales as ρv^2 so slower implosions are sufficient for FI. Use of thicker shells with lower gas pressure reduces implosion velocity, instability growth and the size of the central hot spot at the expense of reduced hydrodynamic efficiency. Cryo -target designs have been developed for ρr ranging from full size (ρr~3gcm^{-2}) down to ¼ scale at Omega, the latter giving ρr~0.7gcm^{-2} as illustrated in figure 10. The FI gain of these implosions has also been modeled using 2D hydrodynamics and ignition by injection of a cylindrical e-beam and is for example, 150x for the full size target. The sacrifice of hydrodynamic efficiency reduces gains by a factor ~0.5x relative to implosions close to the instability limit hence the higher gain estimates in figure 6. Lower ablation pressure and longer pulse drive would give higher efficiency but more instability.

Ignition scale target design has been undertaken for indirectly driven implosions at NIF including study of non -uniform drive and non-uniform shell thickness to reduce the residual central hot spot seen in figure 8 [19]. X-ray driven implosion of hemisphere shells at the pulsed power z-pinch x-ray source Z has also been modeled [20]. Direct drive designs have been developed for conceptual new FI facilities, Firex II (ρr=1.2 gcm^{-2}) and Hiper[21] (ρr=1.7 gcm^{-2}) which are discussed later. Ideal hydrodynamic solutions fully eliminating the hot spot have been studied in 1D by analytic and numerical methods[22] but the required initial density and velocity pattern is not fully realizable using laser compression.

The previously described cone- guided implosions at Gekko have been modeled with 2D hydrodynamics[23] and more recently new cryogenic target designs for the FirexI project at Gekko have been developed [24]. Details such as the benefits of low z tamping layers on the outside of the Au cone and shock breakthrough sensitivity to the distance between the cone tip and the center of the spherical shell are currently being investigated in this work. These designs all follow the general scaling law that the driver energy governs the scale with $\rho r \sim E^{1/3}$ so that for example ½ scale targets which can have gains ~100 in FI, require only 1/8 of the driver full scale energy. The choice of scale is important because of its potential effects on coupling efficiency, smaller scales being beneficial by reducing the separation of the cone tip and the dense plasma. Burn efficiency falls significantly below the $\rho r/(\rho r+7gcm^{-2})$ scaling when ρr is <1.5 gcm^{-2}, which limits the utility of <1/2 scale implosions [22].

An experimental test of a thick shell implosion using a CD shell has been made at Omega [25]. A rather high pressure (30bar) of deuterium and He_3 produced D-He_3 fusion protons so that the ρr could be determined from the energy loss of the protons traversing the imploded shell. The data analysis is complicated by premature termination of thermonuclear reaction at 3% of the 1D simulated yield, before peak compression, but peak ρr estimates of 0.26 gcm^{-2} were obtained and modeling suggests this would increase to 0.7 gcm^{-2} with no gas fill.

C. The electron source

The physics of the laser generated electron source is complex but it has been modeled in steadily improving detail using very large scale 2 and 3 D explicit particle in cell (PIC) simulations [26] Figure11 illustrates this class of computation showing the enhanced Poynting flux in a cone and electron generation in a divergent beam. The essential physics occurs at densities from sub critical to a 100x critical density. Such densities are manageable with explicit PIC codes which must resolve the Debye length in space and the inverse plasma frequency in time. They become too slow and demanding of processor storage for higher densities e.g. 300gcm^{-3} which corresponds to 10^5x N_c. It is important to model laser absorption starting with a preformed plasma due to the unavoidable nanosecond pre-pulse energy from amplified spontaneous emission in FI. The density gradient at the critical density has a significant effect on the quasi-

Maxwellian temperature of the generated hot electrons and on the laser absorption fraction[27]. Both temperature and absorption are reduced in steeper gradients. Light pressure steepens the gradient in ~1ps and the energy spectrum changes in time. Mean energies after the steepening, can be well below the previously mentioned ponderomotive potential. This effect is potentially important as it may obviate the need for shorter laser wavelength[28]. The angular distribution of the electrons is also crucial. It is sensitive to geometry and the particular case of cone geometry illustrated in figure 11 is of key importance. The cone concentrates reflected laser light and also guides electrons generated on its walls to its tip via a surface magnetic field[29] launching electrons beyond the tip in a rather wide range of angles[30]. Current PIC modeling of the electron source has good predictive capability.

Numerous experiments have measured key properties of the electron source. Its temperature for 1μm wavelength has been described by an empirical scaling law [31] $kT/1keV = 100(I/10^{17}Wcm^{-2})^{1/3}$ at intensities below $5x10^{19}Wcm^{-2}$ and the conversion efficiency to electron energy has been measured from Kα yields in solid targets with efficiencies increasing with intensity and reaching >30% for FI relevant intensities[32]. More recent better diagnosed and better modeled experiments are updating the earlier work which has been generally accepted as showing that conversion efficiency is satisfactory for FI. Determination of the source temperature and conversion efficiency in full scale FI with 20 ps pulses at $>10^{20}$ Wcm^{-2} will however require higher energy pulses than have been available to date and will strongly influence the issue of the required wavelength of the short pulse laser.

D. Electron energy transport

The 1GA current of electrons entering the compressed plasma challenges understanding of beam plasma interactions and is the major area of current uncertainty in FI. The divergence of electron energy transport is a critical factor influencing the coupling efficiency to the hot spot.

PIC modeling cannot be used as the required spatial and temporal zoning is too small. Hybrid PIC modeling has been developed in which the dense plasma is treated as a fluid by magneto-hydrodynamics (MHD) and the relativistic electrons of much lower density are treated by PIC methods[33]. Fokker Planck modeling of the fast electrons is a variant method that is also used [34].

The physics issues are complex. The injected current is ~10000x the Alfven limit (17βγ kA). At this limit the self generated B field makes the Larmor radius smaller than the beam diameter and stops the beam propagation. Hot electrons entering the dense plasma are initially 100% compensated by a return current of background electrons [35]. The finite resistivity to the return current sets up an Ohmic E field which slows and can reflect the hot electrons. There is a growing azimuthal B field with dB/dt ~ curlE and associated growth of net current . This B field can pinch or collimate the electrons [34]. A similar process can also occur on small spatial scale at local peaks in the current density to cause resistive Weibel – like filamentation[36]. Instability growth rates are highest for wavelengths near the skin depth but filaments attract and merge leading to larger scale filamentation. Axial current density perturbations drive the electrostatic two stream instability[37]. All the instabilities are stronger where the ratio of hot electron density to background density is higher i.e. where the beam enters the plasma at lower density. At the entry surface an oppositely directed azimuthal B field grows with dB/dt ~ gradNxgradT from the electron fountain effect. An E field drives surface plasma blow off and electrons can be trapped in the B field and drift radially at high velocity ~ ExB [38].

This panoply of complications makes experimental study difficult and the situation is exacerbated by the temperature dependence of dense plasma resistivity. It peaks in the range 30 to 100eV as shown in figure12 and at higher temperatures decreases as $T^{-3/2}$ in the classical plasma or Spitzer regime. The compressed DT fuel has very low resistivity and negligible Ohmic effects whereas experiments with solid targets have typically generated temperatures near the resistivity peak with Ohmic potentials comparable with the electron energies and rapid growth of B fields thus maximizing the complicating phenomena .

Many experiments have measured transport in simple foil targets including solids, foams , layered foils, low mass small area foils and oblique foils. Hollow cone targets, cone /foil targets , cone wire targets , nail head wire targets and end on wire targets have also been studied. Preheated targets have been used to avoid rapid changes of resistivity in targets that are initially cold. These include shock heated foils and shock compressed foam . The motivation has been to understand transport and find simpler situations to benchmark numerical models[39].

New diagnostics which have been developed to show the spatial patterns of transport including imaging of Kα emission, streaked optical pyrometry, xuv imaging and imaging of transition radiation, the latter three being rear surface diagnostics. Electron energy spectra have been measured for electrons escaping into vacuum[40].

Where the geometry has been constrained as in cone /wire targets the transport in the wire has been seen to have penetration limited by Ohmic potential[40]. On simple slab targets divergent transport has been observed with 20 to 40° cone angles [41]. The diverent transport is complex to model and is critically influenced by the electron source characteristics. The divergence is a crucial factor determining the coupling efficiency .To date it has not been possible to use PIC description of the laser induced electron source and couple it with hybrid PIC transport modeling though work is ongoing to achieve this. Transport cone angle in FI targets therefore remains a critical area of uncertainty.

Hybrid PIC modeling with arbitrary assumptions about electron injection is being used to assess what may happen[42]. Several studies have modeled the Gekko integrated experiment with hybrid PIC and Fokker Planck models with heuristic injected electrons but none so far have made an ab initio calculation of the electron source[43] . Fig 13 shows for example that ignition of adense DT plasma is achieved with filamented divergent transport albeit with very high energy, 60 kJ in the e-beam.[44]

E. Channel formation, hole boring and super penetration

Although it was proposed first, the channel and hole boring scheme has received rather little attention[44]. Recently some advanced 3D PIC modeling of channel formation has been carried out showing that a channel can reach the critical density. If a shorter wavelength were used this could perhaps give penetration close enough to the dense plasma, but for the same ponderomotive expulsion, the intensity would have to be scaled to conserve $I\lambda^2$. Otherwise hole boring by the light pressure I/c is required to push the critical density close to the dense fuel. The problem of long required pulse duration at high intensity and energy deposition by absorption of the hole boring laser radiation causing back pressure and preheating of the target is essentially unsolved. A variant idea is to rely on 'super-penetration' by the main ignitor pulse which experiences relativistic self focusing giving enhanced hole boring. Some experimental work has shown the process occurring in a preformed plasma and a small effort has gone into some integrated tests with the Gekko PW laser irradiating an implosion with no cone[45]. Recent PIC modeling has reexamined the process but has suggested however that the intensity enhancement by self focusing will create the problem of too high electron energy . Many unresolved questions remain for this approach to FI. It is simpler to test than the cone schemes and experiments are anticipated with the new Omega EP facility discussed later, which is specifically equipped with hole boring pre-pulse capability.

F. Proton fast ignition

Proton fast ignition is an option for FI with any type of compression driver and the concept has recently been reviewed in detail[46]. The ignition conditions are well established as noted in section IIIA. The hot spot energy and dimensions are the same for electrons or protons. A new factor is transit time spread and the increase of proton range with temperature of the hot spot. The fastest protons arrive first heating cool fuel and 15MeV protons have a range equal to the hot spot ρr. Later arriving lower energy protons have optimal range for energies as low as 3 MeV, as the temperature rises to the ignition level of 10keV. The useful range of proton energy is therefore extended by the temperature variation of the range. All protons must arrive within the 20 ps inertial confinement time so the source to hot spot distance should be <1mm to take full advantage of the useful range of energies. The expansion of the proton plasma takes the form of a quasi - exponential self similar rarefaction wave with the leading edge having the highest velocity and a linear decrease of velocity in the following plasma. The aggregate energy spectrum is quasi -Maxwellian with a high energy cut off at the leading edge of the expansion where there is a Debye sheath[47]. The required ignition energy in the beam for fuel at 300gcm^{-3}, has a weak minimum in the quasi Maxwellian temperature of the protons and 3MeV is optimal giving a 17 kJ energy requirement at 300gcm^{-3}.

The critical issues are conversion efficiency and diameter of the focused plasma jet. Measured conversion efficiencies in unoptimized conditions range from 1% to 10%. Optimum efficiency is obtained by minimizing collision loss in the source foil relative to adiabatic loss to the proton plasma expansion. Hybrid PIC modeling of conversion shows that a low mass per unit area foil, a high electron temperature and a proton rich layer can convert up to 50% of the hot electron energy to proton plasma kinetic energy[42]. Any pre-cursor plasma formation at the rear surface of the foil quenches the formation of the proton plasma jet[48]. The consequent need to protect the rear surface of the foil from shock break out due to pre-pulse on the front surface limits the minimum foil thickness and therefore the maximum efficiency. Experimental tests with optimized source foils are advancing and should confirm adequate laser to plasma jet efficiency ~ 15%. Focusing was demonstrated first with a 10J, 100fs laser irradiating a tightly curved 350 μm diameter hemisphere shell target [49]. A small focal spot relative to the shell diameter, was used to generate ~4 MeV hot electron temperature. The proton plasma expansion velocity was consequently maximum at the center and slower at the margins and the flow lines were deformed relative to perfect perpendicularity, diverging more at larger radii with lower energy protons having higher divergence. The focusing is therefore degraded and moved beyond the center of the hemisphere. Experiments with the Gekko[50] and Vulcan PW lasers[51] followed with similar results but higher temperatures produced by proton heating, the latter being illustrated in figure 14. Modeling with the hybrid PIC code LSP shown in figure 15 indicates that better focusing can be obtained with more uniform irradiation. For example a 50 μm diameter laser focal spot on a 100 μm diameter shell produces a 10 μm plasma jet focus while the same focal spot on a 350 μm shell shows significant effects of non uniformity[51]. Scaled experiments should be adequate to show whether the focal spot requirements with an in-cone source foil can be met and the first test of in-cone focusing has been made recently. A conceptual design for ignition with in-cone uniform proton plasma expansion produced by uniform laser irradiation is shown in figure 16.

Consideration of the use of ions for ignition is not limited to protons and it has been suggested that for example carbon ions accelerated in a similar fashion to protons might have advantages[52]. A rather different hydrodynamic concept is hyper-velocity impact ignition[53] in which a thin spherical shell segment in the cone is ablatively accelerated by a longer duration lower intensity laser pulse to $>10^8$ cms^{-1} and ignites the hot spot on impact. The main issue in this scheme is whether instabilities will break up the shell before it reaches the required velocity.

V. Progress in laser technology

There has been very rapid progress for two decades both in new technologies for short pulse lasers and in building more advanced short pulse facilities. These developments have recently been reviewed[54]**.**

A. New technology

The development of high power short pulse lasers using chirped pulse amplification (CPA) and compression with large area diffraction gratings has been rapid since CPA was invented in 1985[55] . The first petawatt laser[56] (500J in 500ps) was enabled by an advance in holographic grating fabrication which provided 1m diameter gratings of high efficiency using Au coating of sinusoidal gratings lithographically printed into a polymer resist on optically flat substrates. Used in two grating compressors they have ~65% through put efficiency. Stable mode locked pulse generation in Ti sapphire lasers provides seed pulses of typically 1nJ energy which after stretching to nanosecond duration for CPA in Nd glass amplifier chains, can readily be boosted to kJ energies. For example 20x20cm amplifiers used in NIF can deliver up to 20kJ in multi-ns pulses at 1.05 mm. The amplification of spontaneous emission in Nd glass creates precursor energy at typically 10^{-4} of the main pulse energy in a one or two ns window ahead of the main pulse when optical gates are open to transmit the main pulse. The use of optical parametric amplification (OPCPA) in the early amplification stages up to ~1J, has reduced the pre-pulse energy fraction by an order of magnitude to 10^{-5} and is the standard now for PW lasers[57].

Multi layer dielectric (MLD) diffraction gratings were developed by ion beam etching of deep rectangular grooves via a lithographically formed resist mask into a dielectric layer on top of a multi layer dielectric mirror[58]. These gratings have higher efficiency ~95% and higher damage threshold. Au grating damage is pulse length independent at ~0.4 Jcm^2 whereas MLD grating damage threshold increases as $t^{1/3}$ and is ~4Jcm^{-2} at 10 ps. MLD gratings have now been fabricated in sizes up to 40x80 cm and their higher efficiency allows use of 4 grating compressors which fully correct chromatic separation in the beam from 2 grating systems. In order to take full advantage of the large aperture of Nd glass lasers, tiling of gratings has been developed in which two or three gratings side by side are precisely controlled in tip tilt and piston motions to function as a single grating [59]. This has allowed designs of new facilities under construction to specify up to 3kJ short pulse generation in a single 40x40cm beam. When multiple beams are used for higher energy and focused to a common focal spot their relative phases determine the focal spot pattern. Random phases produce a speckle pattern within the diffraction envelope of one beam. Uni-phase operation produces a single focal spot at the diffraction limit of the total angular aperture (more precisely the Fourier transform of the near field pattern which is sensitive to the gaps between the beams). Phase control of multiple large mirrors is now used in astronomical telescopes and is being adapted to lasers in R&D for new facilities under construction.

B. Laser facilities

PW lasers (~ 500J, 500fs, 1.05 μm) using 1m Au gratings include the original Nova PW laser (now shut down), the RAL Vulcan PW in the UK [60] and the Gekko PW in Japan[61] (now shut down). PW lasers using MLD gratings without tiling to generate 200 to 500J pulses, include the new Titan laser at LLNL, the LULI upgrade PW laser in Palaiseau , France, now nearing completion and the Phelix PW laser being built at the GSI laboratory in Darmstadt, Germany. These lasers are all coupled to kJ class long pulse beam-lines and support physics studies relevant to FI.

Two major new facilities are being built with features designed specifically for integrated experiments in FI research, namely Firex I in at ILE in Japan and Omega EP at LLE in the USA.

Firex I will generate 10kJ, 10 ps pulses from 4 beam lines with 40x40 cm amplifiers. It has an OPCPA front end and the compressor will use MLD gratings tiled in pairs with 4 grating compression. The 4 beams will be combined in uni-phase and focused at f/6 into the existing Gekko 12 beam implosion target chamber where 5kJ at 0.53 μm is used for compression. Firex 1 will begin operation in 2007 and cryogenic DT experiments with the 4 beams in uni-phase at 10kJ are planned for 2010 .

Omega EP is a major upgrade of the 60 beam 30kJ, 0.35μm Omega implosion facility. It is now under construction with the layout shown in figure 17. A new building houses four NIF- like 40x40cm beam lines two of which are provided with CPA and grating compression. The compressors are in a 4 grating configuration and each grating is a triple tiled assembly of MLD gratings designed to deliver 2.5 kJ in 10ps. The other two beam lines generate 5 kJ nanosecond pulses at 0.35 μm. A new target chamber is provided for 4 beam experiments. The two short pulse beams will also be combined and fed to the 60 beam implosion target chamber where they will be focused with an f/2 off axis parabolic mirror for integrated fast ignition experiments. EP will begin operations in 2008 and user experiments will begin in FY09.

The LIL facility at the CEA laboratories near Bordeaux in France already has 8 NIF -like beam lines generating 0.35μm nanosecond pulses. A new beam line is being added for the Petal laser, which will generate 3.5 kJ, 500fs pulses. Petal uses novel two stage grating compression with pre-compression by transmission gratings in air and final compression by MLD gratings in vacuum. It will be the most powerful PW laser when operating in 2010 and with the LIL laser will support integrated FI experiments.

A 2kJ PW laser based on a single NIF like beam and an MLD grating compressor is being developed at the Z Beamlet laser at the Sandia Laboratory in the USA. It will be coupled to the upgraded z-pinch x-ray facility Z in 2009, providing capability for integrated fast ignition experiments .

The NIF has provision for four beams in a quad to be converted to short pulse CPA operation in the NIF advanced radiography (ARC) project[62]. The changes are relatively minor: a new mode locked fiber laser front end ,modifications to preamplifiers and to plasma electrode Pockels cell optical gates, deviation of the beams to an available near equatorial port on the target chamber, installation of two vacuum compressor vessels each housing twin compact folded 4 grating MLD compressors and f/20 focusing with an off axis parabolic mirror. The gratings will be paired so that the first beam will operate in two rectangular 20x40 cm sections providing 1.2kJ, 10 ps pulses designed for pulsed radiography. A similar second beam will bring 4 pulse capability for radiography. Specific to fast ignition is current R&D directed to uni-phase operation of all 4 beams of the quad which when focused together would have an effectively f/10 focal spot with 12.9 kJ in 10 ps illustrated in figure 18.

VII. Next steps in target physics and laser technology

The next phase of FI research will be crucial in assessing its potential. Hydrodynamic designs for the cone guided implosion electron ignition concept will be optimized by minimizing the hot spot and the distance between laser absorption and the ignition region and will be tested at Omega and Gekko. Efficiency of proton generation in proton focusing will be optimized using smaller scale facilities such as Titan with the goal of reaching 15%. The focused proton plasma jet diameter will be minimized in sub-scale experiments with the goal of demonstrating 35 μm capability in ignition experiments through self similarity. Channeling and super penetration will be assessed through modeling and sub- scale experiments. Down selection between the options is probable. Integrated codes are being developed and will be used to design integrated experiments at the major FI laser facilities Omega EP, FirexI and NIF ARC quad . These experiments will determine coupling efficiency to the hot spot and will benchmark the integrated codes. The codes will then be used to design ignition experiments.

The issue of scaling of coupling efficiency will be central in these experiments. The original Gekko expts produced a 50 μm diameter compressed plasma at 50 gcm^{-3}. FirexI aims at compressing DT plasma to $\rho r \sim 0.3$ and density up to 300gcm^{-3} at diameter < 50 μm . Omega EP will compress to ρr=0.7gcm^{-3} at 300-500gcm^{-3} also at diameter <50μm . Both will give important tests of coupling efficiency in a ~¼ full scale situations where the compressed plasma is comparable to or smaller than the ignition hot spot. Firex I should produce temperatures approaching the ignition level. Omega EP will produce only ¼ the temperature at Firex I but will measure coupling efficiency to more precisely driven implosions. The NIF/ARC quad will be capable of compressing plasmas to full scale (200 μm diameter) or down to half scale. NIF experiments will determine coupling efficiency to a hot spot which is a minor fraction of the whole compressed plasma under conditions relevant to high gain fast ignition. All these experiments will provide important benchmarking of integrated codes and thus enable accurate design of high gain ignition.

The integration of Hydro, PIC and hybrid PIC modeling is a major challenge in multi-scale computing and at present two suites of codes are being developed for this purpose . At LLNL the code linkage[63] is between Lasnex and Hydra for hydro, Z3 for explicit PIC and LSP for hybrid PIC . The linkage is based on transfer of data by via the Python language. At LLE[64] the fast ignition integrated interconnected code FI^3 illustrated in figure 19 links hydro modeling with PINOCO, PIC modeling with FISCOFF and Fokker Planck transport modeling with FIBMET. These integrated codes are still under development. In Europe integrated modeling development is starting in connection with the HiPER project discussed here later.

VIII. Demonstration of high gain FI

Demonstration of high gain FI will require a well benchmarked integrated design or designs, with requirements that are realizable with low risk. Cryogenic target fabrication will be needed and a suitable laser facility.

Cryogenic spherical shell targets have already been developed for CHS ignition. R&D has been started on targets with cones. For Firex I a fill tube wetted foam design is being developed[65] , for Omega EP the sealed beta layering method used for CHS targets is being adapted[66] and at Z a liquid filled double shell hemisphere target is envisaged[67] as a special case of cone angle 180°.

There are two conceptual new facilities under consideration. The smallest is the 50kJ, 0.35 μm long pulse and 50kJ, 1.05μm short pulse Firex II in Japan[68]. More aggressive is the 300kJ, 0.53 μm long pulse and 70kJ short pulse (1st, 2nd or 3rd harmonic TBD) HiPER in Europe[69]. Both use long pulse energies giving sub scale compressed plasmas relative to full scale 3 gcm^{-2}. Firex II is aimed at ignition at ~1/3 scale with gain~10 and Hiper at about half scale with higher gain ~100. Both assume that the coupling efficiency will be high enough to allow their relatively low short pulse energy to achieve ignition. In the case of HiPER the wavelength of the short pulse is still regarded as TBD. A lower cost option which could be available earlier, is adaptation of a major ICF facility for FI. Conceptual engineering study at NIF suggests that 5 quads could be directed into a 30° cone giving 65 kJ in 20 ps at 1.05 μm. 2015 is probably the earliest that FI could be demonstrated at NIF.

Construction of any these facilities is a major undertaking and will be conditional on good results from FirexI, Omega EP and the NIF ARC quad and also on integrated designs indicating the feasibility of ignition at acceptable risk and cost.

IX Risk assessment for high gain FI

The 200kJ to 1 MJ long pulse laser (or z-pinch) driver technology required for high gain FI is available and presents no risk. The short pulse laser energy requirement is uncertain but adaptation of long pulse beam lines for short pulse operation at a few kJ /beam with tiled MLD grating compressors is at an advanced stage of development. There is little risk in generating the required pulse energy at 1 μm wavelength in multiple beams. Combining the beams with phase control is at early R&D stage and has not yet been done for high energy beams. Laser specific factors such as intensity dependent non linear phase changes and large pulsed thermal energy input may add difficulties and create some relatively minor risk which can be mitigated by R&D. If however the short pulse is required to be at 2ω or 3ω new issues will arise. Frequency conversion for long pulses is well developed and could be used if grating compressors were adapted operate at 2ω, but this would require significant grating fabrication R&D. Alternatively very thin harmonic conversion crystals could give post compression conversion also requiring R&D. Different types of laser such as the KrF Raman laser at 268 nm[70] could also be used. In any event there would be moderate risk and a need for R&D investment to develop high energy short wavelength short pulses.

If cones are required then cryogenic DT targets with cones must be developed. None of the three approaches being considered has been significantly developed but cryo-engineering is mature and appropriate R&D investment should solve the problem with low risk.

The main risk for FI lies in the target physics where there are still substantial uncertainties in laser to ignition hot spot coupling efficiency which could make the required short pulse laser energy significantly higher than say 150kJ and short wavelength may also be required. This risk is high based on current knowledge. For electron ignition via a cone it can be mitigated by use of reduced scale targets which reduces the critical separation distance between laser absorption and the hot spot. This limits gain but on the positive side, allows use of a smaller driver. Innovative hydrodynamic design may also reduce this crucial distance at a given scale. Proton FI could avoid the electron transport issues but it is as yet only an early stage concept requiring verification that efficiency and plasma jet diameter can meet FI requirements. It is very high risk. Channeling and super penetration appear at this time to have extremely high risk. Little has been demonstrated experimentally and modeling has not yet shown successful penetration of the mm scale plasma surrounding the dense core. The significant >500μm distance between critical density for a 1μm laser and the dense core also suggests that shorter wavelength would be needed for channel formation and it seems unlikely that super penetration alone could be successful.

If the ignition laser requirements are too severe then fast ignition will not be possible by adapting existing facilities and the concepts for new facilities will have to be modified. Longer term the cost of short pulse energy may not be so much higher than long pulse energy that FI with an ignitor laser energy of a few 100kJ is out of the question. The larger the short pulse energy requirement however the longer is likely to be the delay before high gain FI could be demonstrated. Depending on the outcome of its development, direct drive CHS ignition could be developed in preference to FI if the required short pulse ignitor laser energy is excessive .

X. The route to Inertial Fusion Energy

Assuming that first CHS ignition then high gain FI are successfully demonstrated there will be greatly enhanced interest in the use of ICF and particularly FI for IFE. A sub MJ driver with efficiency ~10% giving gain >100 is very attractive for a power plant. At present power plant scenarios for ICF are being studied internationally at a modest level.

Several conceptual plants for CHS ignition have been outlined[71,72]. Concepts specific to fast ignition are a more recent development, for example KOYO –Fast, being studied in Japan[73]. There is associated R&D on the separable technical aspects including rep rated laser technology, fusion chamber technology, robust final optics, target injection and tracking and target fabrication[74]. In the US high average power laser project (HAPL), the high repetition rate high efficiency lasers Electra, a UV electron beam pumped KrF gas laser[75] and Mercury, an infrared diode pumped solid state laser[76] are being developed and have operated successfully for >25000 shots. These prototypes could lead on to future modules of a power plant. A summary statement is that while no insoluble problems for an FI power plant have been identified neither has significant engineering design been attempted.

XI. Conclusions

This review shows the potential of fast ignition but identifies the challenges and risks associated with its development. The next few years will clarify the situation and if outcomes are favorable, will identify a path to high gain ICF and ultimately fusion energy.

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Figure 1 Comparison of ICF indirect and direct drive compressing the ablator/DT fuel shell .

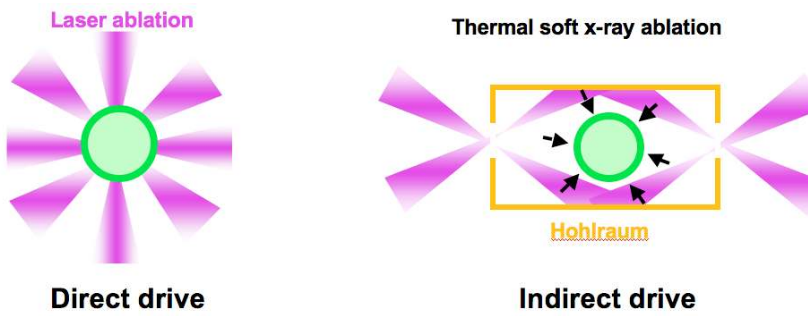


Figure 2 . Comparison of ICF ignition of the compressed DT fuel by CHS and FI methods

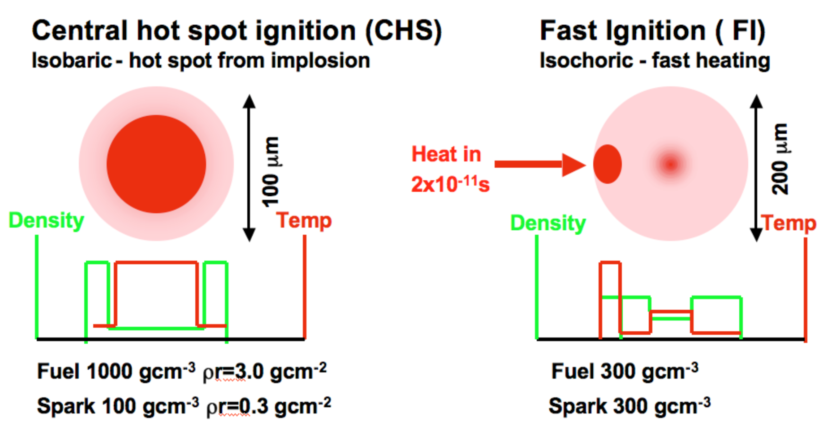


Figure 3 Cartoon of the hole boring concept first proposed for fast ignition

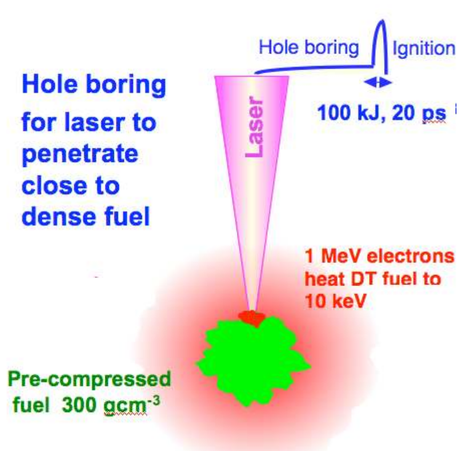


Figure 4 The cone guided implosion FI concept for electron and proton ignition

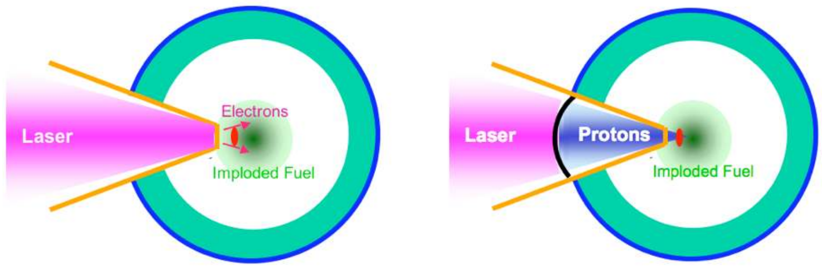


Figure 5 Simple model gain estimates for direct drive fast ignition targets compared with CHS ignition designs for NIF . The FI gain curves are labeled with fuel density , energy and $I\lambda^2$ in the ignitor laser beam assuming a wavelength of 0.53 μm

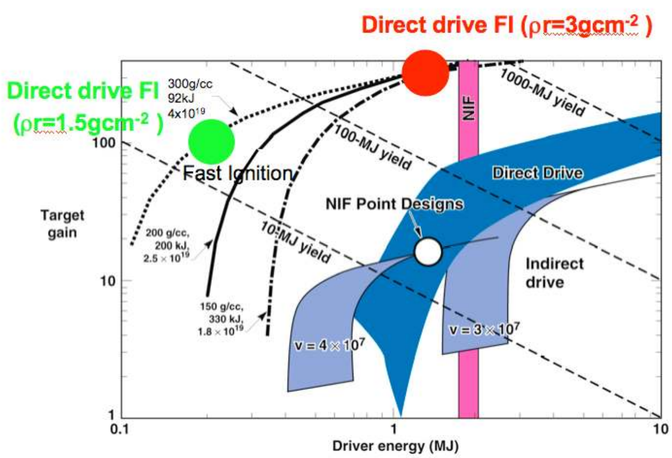


Figure 6 An example of Rayleigh Taylor instability inside and outside of an imploding shell from 3D modeling with the HYDRA code .

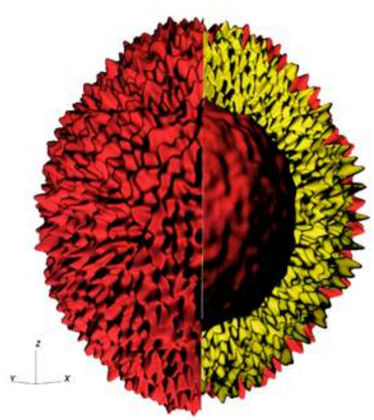


Figure 7 The first integrated FI experiment using the cone guided implosion scheme .Left :the target . Right: the neutron yield with modeling for 30% and 15% coupling efficiency .

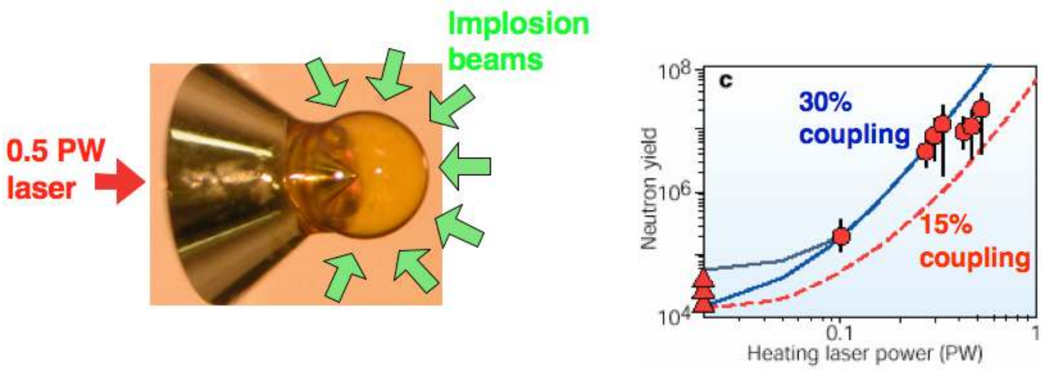


Figure 8 The first hydrodynamic design of a cone guided implosion using the code Lasnex . The target is indirectly driven with a peak hohlraum temperature kT=250eV . The fuel density at peak compression is shown on the right

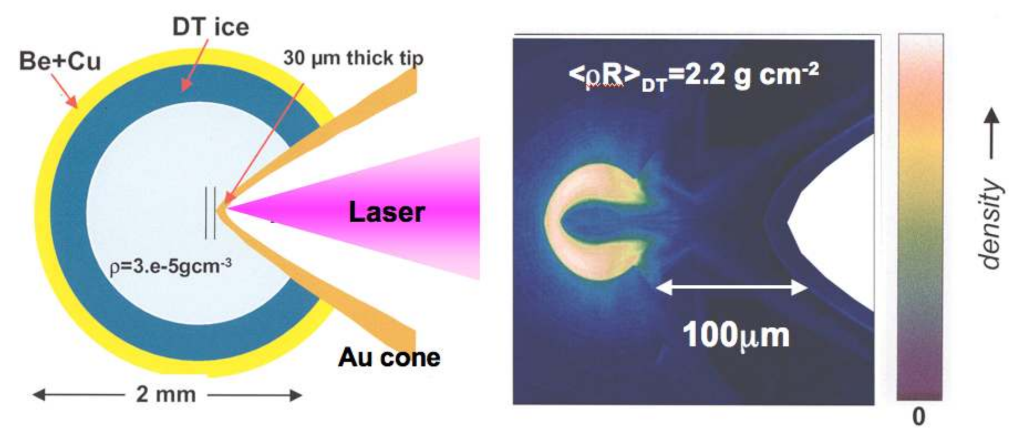


Figure 9 Cone guided implosions of CD shells at the Omega laser . Left: indirect drive radiographs simulated and experimental . Right: the same for direct drive . Center:design and modeling of density .

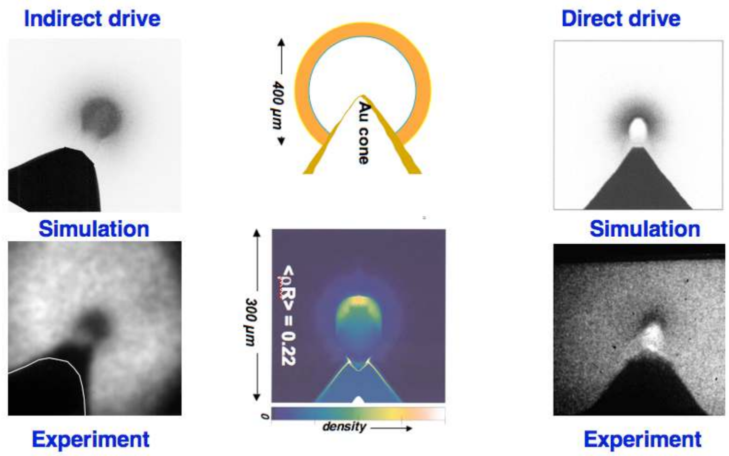


Figure 10 DT wetted foam shell designs producing FI densities of 300-500gcm-3 from full scale to ¼ scale

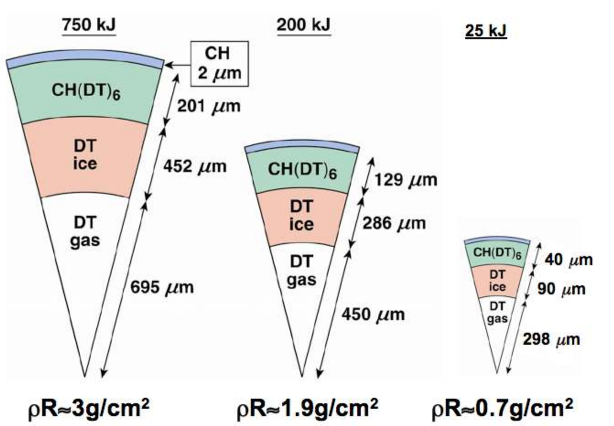


Fig11 Example of 2D PIC modeling of absorption and electron generation using the Z3 code

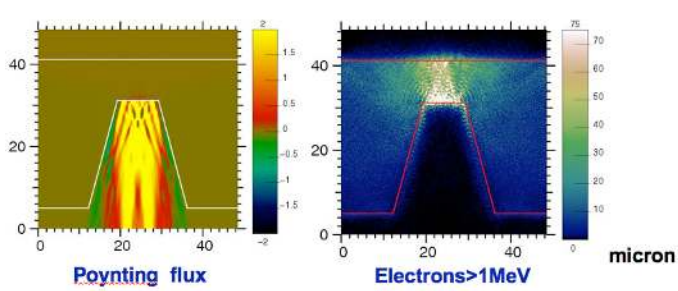


Fig12 Resistivity of plasmas relevant to FI research . The Ohmic limit is where FI required current density produces 1MeV Ohmic potential in 100 μm

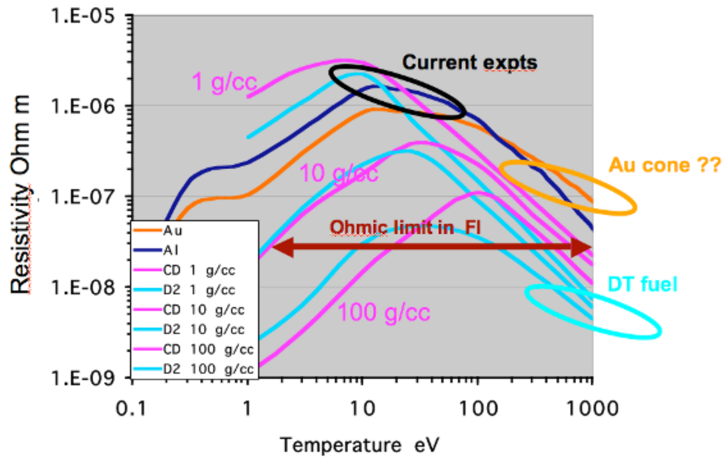


Fig 13 Electron transport modeled by hybrid PIC and showing ion temperature at the end of the pulse with ignition of a ½ scale FI target design for the HiPER project . 60kJ, 10 ps , 22^o divergent electrons are injected with mean energy 2.5 MeV from a 40 μm spot into a compressed plasma with half peak density contour at the dotted circle and having 400g/cc peak density . Ion temperature color map shows is $\log_{10}$ Ti from 2.8 to 4.1 . Cross cut maop is just inside the dense plasma (vertical line)

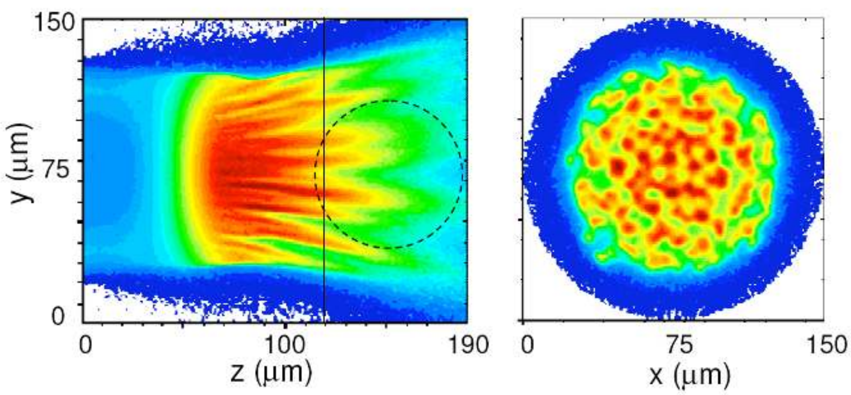


Figure 14 Proton focusing and heating with the Vulcan PW laser . Streaked image of 68eV emission from rear surface of 20μm CD target shows prompt pulse of proton heating and static xuv image at 256eV shows diameter of heated region .

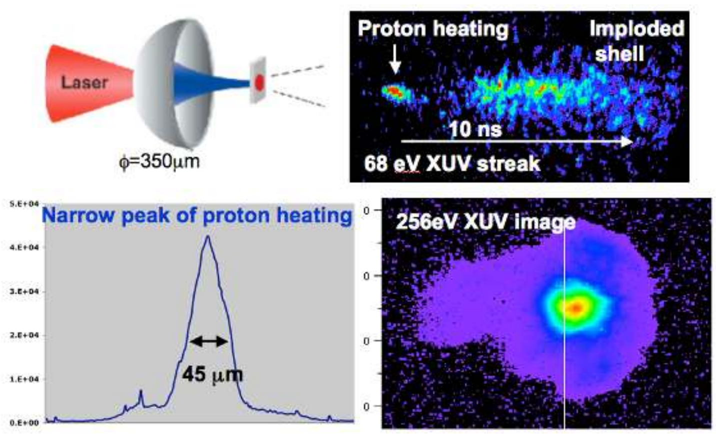


Fig15 Modeling of proton focusing with hybrid PIC code LSP . Two cases both with 50 μm fwhm laser irradiation of hemisphere shells .

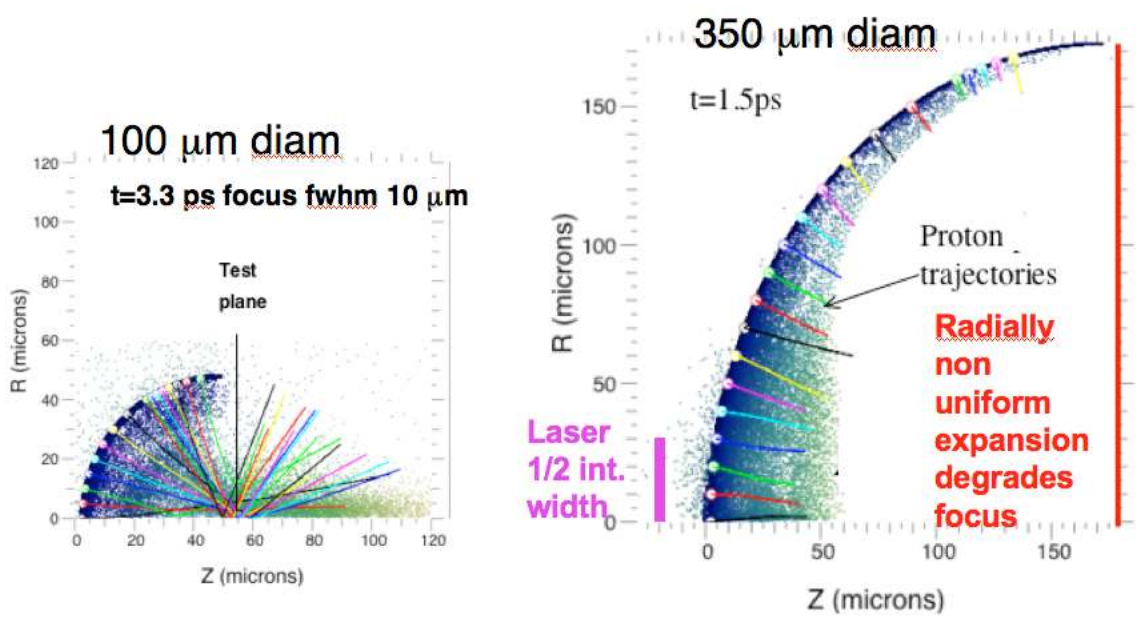


Fig 16 Conceptual proton fast ignition

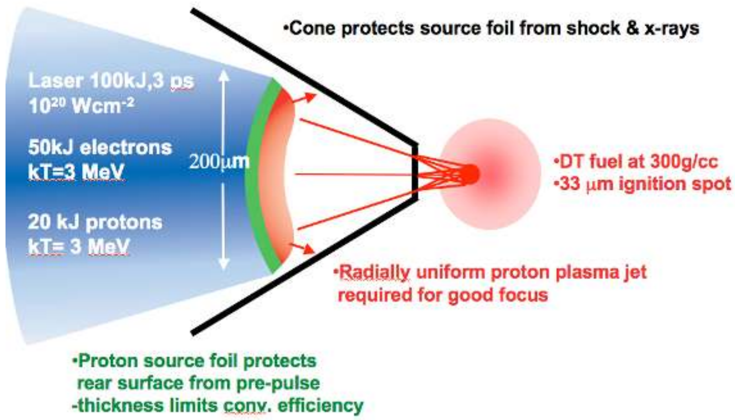
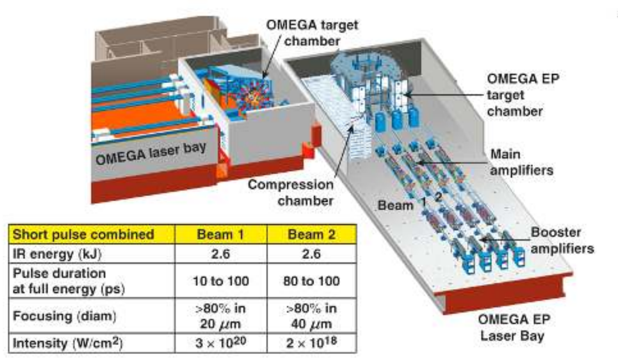


Fig 17 The Omega EP facility



Short pulse combined	Beam 1	Beam 2
IR energy (kJ)	2.6	2.6
Pulse duration at full energy (ps)	10 to 100	80 to 100
Focusing (diam)	>80% in 20 μm	>80% in 40 μm
Intensity (W/cm^2)	3×10^{20}	2×10^{18}

Fig 18 Uni-phase operation of 4 short pulse beams in a quad of the NIF would produce a high quality focal spot for tests of coupling to ignition targets

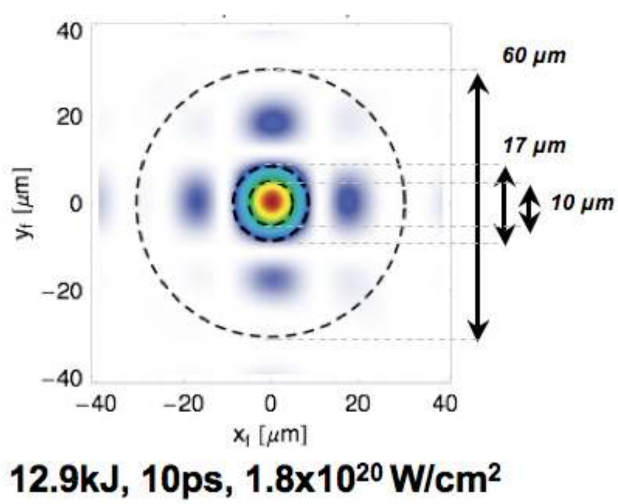


Fig 19 The FI^3 integrated modeling codes being developed for the Firex project