UCRL-CONF-207839

Review of progress in fast ignition

max tabak, Richard Town, Barbara Lasinski, Richard Snavely, Dan Clark, Scott Wilks, michael Key, Steve Hatchett, Richard Stevens, E.Michael Campbell, K.Mima, Kazuo Tanaka, R.Kodama, Stefano Atzeni

November 9, 2004

American Physical Society/Division of plasma Physics
Savanah, GA, United States
November 14, 2004 through November 19, 2004

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Marshall Rosenbluth's extensive contributions included seminal analysis of the inertial fusion program. Over the last decade he avidly followed the efforts of many scientists around the world who have studied Fast Ignition, an alternate form of inertial fusion. In this scheme, the fuel is first compressed by a long pulse driver and then ignited by the short pulse laser. Due to technological advances, external energy sources (such as short pulse lasers) can focus intensity equivalent to that produced by the hydrodynamic stagnation of conventional inertial fusion capsules. This review will discuss the ignition requirements and gain curves starting from simple models and then describing how these are modified, as more detailed physics understanding is included. The critical design issues revolve around two questions: How can the compressed fuel be efficiently assembled? And how can power from the driver be delivered to the ignition region? Schemes to shorten the distance between the critical surface and the ignition region will de discussed. The status of the project is compared with our requirements for success. Future research directions will be outlined.

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

I. Introduction

Fast Ignition[1] is a form of inertial fusion in which the ignition step and the compression step are separate processes. The invention of chirped pulse amplification[2] of lasers spurred research in this area because these lasers can, in principle, supply energy to the fusion ignition region as fast as the convergence of stagnating flows can for the conventional ignition scheme. The delivery of this ignition laser energy is mediated by the transport of relativistic electrons produced in the laser-plasma interaction. Another variant of this scheme uses protons[3] driven by these fast electrons to deliver the energy to the fuel. Fast Ignition offers the possibility of higher gains, lower driver energy and cost required to achieve economically interesting gains and lower susceptibility to the effects of hydrodynamic mix than the conventional inertial fusion scheme. Researchers around the world have studied this fusion scheme intensively for the past dozen years. Marshall Rosenbluth encouraged this work and contributed to it. This report will review this scheme, the progress made over the past decade and possible directions for the future. The plan of this paper is as follows: section II describes ignition requirements and a gain model. Section III describes a typical implosion used to assemble fuel and how this might be modified. Section IV describes results on the coupling of laser light to slabs and the subsequent transport of electrons. Section V describes various techniques to transport energy between the nominal critical surface and the compressed fuel. Section VI summarizes the report.

II. Ignition requirements and gain models

Fuel ignition requires that we heat a sufficiently large region to the ignition temperature. This ignition temperature depends on the ignition region size given by its column density, $h = \int \rho dR \approx \rho R$. The hotspot energy requirement is then: $E_{ign} = 144 \left(Z+1\right)/A \, MT$, where $M = 4\pi/3\left(\rho R\right)^3/\rho^2$ and ρ is given in g/cm^3 ,T in keV and E_{ign} in MJ. In conventional inertial fusion, a low density hotspot and ignition region is surrounded by a relatively cold and dense main fuel region, where the bulk of the yield is produced. The heating of the hotspot and the compression of the main fuel to high density happen simultaneously as the kinetic energy of the imploding shell is converted into internal energy of compressed fuel during stagnation. Because the hotspot and the main fuel are sonically connected, their pressures are approximately equal. The minimum ignition requirements (T and h) depend on how well energy is confined in the hotspot. The losses can include radiation, electron conduction and hydrodynamic work. In an isobaric configuration, the hotspot is tamped and its hydrodynamic losses are limited during ignition. In addition, some self-heating during the implosion reduces the energy that must be delivered to the hotspot for ignition. In the isochoric configuration used in Fast Ignition, the ignition region is far out of pressure balance with the surrounding fuel, so hydrodynamic losses can be significant.

Atzeni and collaborators[4] by performing a series 2D simulations where energy is injected into precompressed D-T fuel found that the ignition energy in an isochoric configuration was approximately 5 times greater than that for isobaric ignition. This corresponds to h=0.6gm/cm^2 and T=12keV. Figure 1 shows the ignition windows in energy,power and intensity for various fuel densities. The minima for these quantities for deposition ranges between 0.3 and 1.2 g/cm^2 can be parameterized as functions of ρ:

$$E_{ign}(kJ) = 140\left(\frac{\rho}{100\,g/cm^3}\right)^{-1.85};\; W_{ign}(W) = 2.6\cdot 10^{15}\left(\frac{\rho}{100\,g/cm^3}\right)^{-1};$$

$$I_{ign}\left(W/cm^2\right) = 2.4\cdot 10^{19}\left(\frac{\rho}{100\,g/cm^3}\right)^{0.95}.$$

Preliminary results show that if the ignition energy is used to drive an ultra-high pressure reimplosion of the compressed ignition region instead of directly heating it, the ignition energy can be reduced by at least a factor of 2 with an associated increase in spot size and delivery time.[5]

By combining these ignition requirements with models of directly driven implosions[6,7]; the relation between ignition laser intensity and the temperature[8] of the hot electron distribution: $T(MeV) = (\frac{I_{ign-laser}}{1.2\cdot 10^{19}(W/cm^2)})^{1/2})$; and the particle range is R(g/cm^2)=0.6 T(MeV), we can derive model gain curves[9]. The nominal model assumes a 25% coupling efficiency from ignition laser to fuel with duration and spot size inferred from the ignition requirements given above. Using cones and proton beams to deliver energy to ignition region(see below) breaks the ties between the ignition intensity and laser intensity. Direct illumination produces particles with the longest ranges and hence the largest ignition requirements. Figure 2 shows the dependence of the gain curve on the minimum laser spot size. Note that the nominal model produces gain 100 at about 10% of the energy required from a conventionally ignited directly driven capsule. Table I shows the sensitivity of the gain to various changes in model assumptions.

III. Implosion results

We require an implosion to assemble the fuel into a compact and dense mass.Typical ICF implosions are designed to produce a central high entropy region where ignition occurs. Figure 3a shows density profiles produced during various moments of a typical direct drive implosion. There are two salient features: the critical density(where the plasma frequency equals the optical frequency) is located almost a millimeter from the high density region and the compressed fuel assembles into a high density shell surrounding a central region with ten percent of the peak density. This thin shell is difficult to ignite by injecting heat because it can disassemble in two directions during the ignition phase. In addition, the burn efficiency of the fuel, once ignited, is reduced because its column density($\int \rho dR$) is smaller when distributed as a shell than as a uniform sphere. We can eliminate the central low density region in several ways: 1) introduce a high-Z seed into the center and radiate away the entropy(see Figure 3b). For the implosion shown in Figure 3, this a 10% energy cost. 2) Expel the central gas through openings(either preformed or produced during the implosion) in the shell. See the discussion on cone-focus geometry. Or 3) design the implosion so that with proper pulse-shaping, a shell can be imploded to form a uniform sphere. Self-similar implosion profiles exist that can accomplish this(see figure 3b). Producing the initial state leading to this self-similar implosion remains to be accomplished.

IV. Laser coupling to fast electrons and subsequent transport

Figure 4 shows the conversion efficiency of intense light to forward-going relativistic electrons[10]. These data were inferred from experiments where targets composed of varying thicknesses of aluminum followed by 50 μm molydenum K_α fluor layers and then 2mm thick CH beam stops are illuminated with intense laser light. The K_{α} signals were then compared with predictions of the Monte Carlo code ITS[11] using Maxwellian distributions for the injected electrons. The temperature of the distribution is given by

Because this analysis does not yet include the self-consistent electric and magnetic fields, these coupling measures are underestimates.

Physics at multiple scales affects the transport of the intense relativistic electron beams produced by the laser. For Fast Ignition applications the electron temperature is in the range 0.5-3 MeV, the forward current is a giga-ampere and the forward current density is about 10^{14}A/cm^2. This current leads to large space-charge and induced electric fields that draw a return current approximately equal to the forward current. The return current is composed, in part, of low energy electrons. Scattering of these returning electrons produces a resistive E field=j/σ ~10^8V/cm in aluminum below 100 eV temperature. This field is large enough to produce a runaway electron fraction rate of 10^{12}/sec. Conductivity, background ionization state and equation of state all affect transport properties and depend on atomic scale(10^{-8}cm) physics. Because the current densities are so large, coherent scattering[12] of pairs relativistic electrons off background electrons and ions may increase stopping and multiple scattering relative to incoherent single particle scattering[13].

On the scale of the collisionless plasma skindepth(0.01-10 micrometers) the two-stream and the collionless and collisional version of the beam filamentation instability have growth rates that scale like $(n_b/n_e)^{1/2}\omega_e$. Figure 5[14] shows the scaled energy loss for cold relativistic electron beams as they propagate through background plasmas with densities varying from $10n_b$ to 50_b. These results come from 2D PIC calculations with periodic boundary conditions at all surfaces. The bulk of the beam energy loss corresponds to coalescence events where two filaments join. The energy goes to building the magnetic field. When $\alpha=n_e/n_b = 10$, the energy loss rate corresponds to stopping in a range of $5\cdot10^{-5}$g/cm^2. This is stopping power 10^4 as large as classical. The stopping power decreases as α increases. Eventually the beam energy loss saturates[15] due to magnetic trapping. Finite transverse beam temperature,T, reduces the linear growth rate. Silva,et.al.[15] found, using a waterbag beam distribution , that there is, as shown in Figure 6, a threshold for instability growth that depends on α and T/E_{beam}.

Figure 7 shows the temperature measured at the rear surface of a 100μm thick aluminum slab[16] together with the results of a simulation[17] performed with the hybrid code,LSP[18]. The simulation used the laser intensity pattern, phenomenological coupling efficiencies, and the Beg[19] relation between the laser intensity and the average energy of the electrons produced: $E_{hot}(MeV) = 0.1(I\lambda^2/10^{17}W/cm^2\mu m^2)^{1/3}$. A uniform thermal spread with T=300keV was added to the electron energy distribution. The resistivity used was approximately that given by Lee and More.[20] In particular, no subscale anomalous resistivity model was used. The results were fairly insensitive to the grid resolution of the simulation indicating that plasma turbulence was not the key factor in producing the rear surface pattern.

The beam spot after a 100μm transit had a 72μm FWHM. This width is marginally acceptable. The spot size after a 1mm transit would lead to unacceptably low coupling efficiency to the ignition region. Experiments[21] where embedded K_α fluors are imaged show that the beam spreads with a half-angle of 20-25 degrees starting from a front-surface spot of about 5 times the radius of the nominal laser spot. Also seen spectroscopically was that a micrometer thick front layer was heated an order of magnitude more than the bulk plasma. This localization may be related to the generation of surface magnetic fields driven by ponderomotive pressure.[22]

V. Spanning the distance between the critical surface and the ignition region

We will try to span the distance between the critical surface and the ignition region : 1)by boring a hole through plasma;2) by using hot electron driven proton beams to heat the target; or 3) by separating the ablation region from the ignition laser path with a conical divider. The hole-boring scheme[1] uses ponderomotive pressure, thermal pressure as well as the relativistic increase of the critical density(n_c) with laser intensity to shorten the distance between the critical density and the ignition region. Young,et.al.[23], have shown 80% efficiency in the propagation of 60J of laser energy through plasmas with peak density $0.3n_c$, scale size 500μm over 500 ps with intensity $5 \cdot 10^{15}$W/cm^2. Recently,Tanaka,et.al[24] have propagated a ps pulse of light at 10^{19}W/cm^2 through 10 n_c, with 5% efficiency, demonstrating the relativistic effect as well as ponderomotive hole boring.

After propagating through a slab, some fraction of the relativistic electrons produced in the laser-plasma interaction at the front surface will escape at the rear surface. This will generate a large electrostatic field that in turn will accelerate the hydrogen constituents of the pump oil adsorbed to back surface of the slab or of a hydrocarbon substrate. [25] Because the incident electron current is so large, the peak fields are of order 10^9-10^{10} V/cm at the proton front and have duration a few picoseconds. The efficiency of conversion of laser energy into proton energy as large as 12% has been measured[26] .The bulk of the acceleration occurs in a few microns and is 1-D to first order. Hence proper shaping of the foil can be used to focus the beam to a small spot. Patel,et.al.[27], using the 10J JanUSP laser, focused a proton beam to a 30μm diameter spot from 160μm away and heated the target spot to 23 eV. The energy coupled to the target foil was 0.2 Joules. If this is to become a path to Fast Ignition a number of issues must be resolved: proton production efficiency and spectrum, how efficiency and focusing scale to large energies and pulse lengths, consistency of energy delivery time with ignition durations, and multiple scattering through intervening materials such as hohlraum walls or the tips of cones.

Cone focus geometry provides an open path for the ignition laser.[28] Figure 8a illustrates this scheme. If the shell is asymmetrically imploded, the central gas mass is expelled and the shell assembles into a compact mass with little cone mass entrained by the shell. Figure 8b[29] shows the result of such a directly driven implosion when backlit with 6.7 keV photons and filtered with an iron filter to eliminate self-emission. The initial CH shell was filled with 5 atmospheres of D_2 The compressed core was less than a diameter away from the cone tip.

3D PIC simulations [30] show that the cone also concentrates energy contained in the laser beam and delivers it to the tip of the cone. The light at cone tip was 20 times as intense as that at the inlet plane. The electrons are confined to a skin depth near the inner edge of the cone by a balance of magnetic pinch forces pushing the electrons toward the cone axis and electrostatic sheath forces pulling the electrons back into the cone. This collisionless PIC calculation covered an extent of 14 x 9 x 9 μm^3 for a duration of 50 fs.

The plasma density was $5.5 \cdot 10^{21}/cm^3$. A gold cone(like that used in experiments) when ionized 30 times has an electron density of $1.8 \cdot 10^{24\wedge}/cm^3$. A hybrid PIC simulation[31] where 2 MeV electrons are uniformly injected parallel to the cone axis with a temperature of 1 MeV into a gold cone with linear dimension 100 μm over 2ps shows electron confinement within a collisional skin depth(please see Figure 9). However, the transfer efficiency from surface of the cone to the tip was only about 10%. Multiple scattering of the relativistic electrons in solid gold folds the path so much that these electrons can only travel 40 μm before depositing their energy.

Experiments at Osaka University[32] measured ultraviolet photons emitted from the rear surface of a slab. A factor of three intensity increase was observed when a cone was attached to the front of the slab. Energy collection efficiency will be optimized by varying collector shape, material and density.

Integrated experiments[33] showed that 25% of incident laser energy could couple to a compressed core. A shell of CD was imploded around a cone of gold with 1.2-2kJ of 0.53 μm light. The shell was compressed to a blob with radius 15μm from an initial radius of 250 μm to density 80-100 g/cm^3. The blob rested on the cone tip. When a $3\text{-}6 \cdot 10^{14}$ W of laser power was injected down the cone, up to a 1000-fold increase in neutron yield over the yield without laser injection was observed(see Figure 10). When the time of laser injection was varied relative to the time of peak shell compression, the peak neutron yield occurred when the two times coincided. The neutron spectrum corresponded to the D-D fusion peak with a thermal width corresponding to an ion temperature of $0.86 \pm 0.1 keV$. The temperature inferred from the slope of the free-bound continuum slope was $1 \pm 0.1 keV$. These temperatures correlated well with the neutron yield. If this good coupling can be maintained for larger systems, high gains can be achieved with a total of several hundred kilojoules.

VI. Summary

Integrated gain models show that high gain at sub-megajoule scale can be achieved with the coupling efficiencies demonstrated in recent experiments. There are multiple ways to assemble compressed fuel without a central low density region. The coupling of laser energy to forward-going electrons is 20-60%. There are multiple ways to deliver laser energy to the fuel:hole boring,proton beams and cone focus geometry. Currently, the most successful of these is the cone geometry but further optimization can lead to reduction in the threshold for high gain. A number of new petawatt laser-implosion system combinations are due to come on line in the years 2007-2008: FIREX at Osaka with 10kJ of shortpulse energy; Omega EP at the University of Rochester with 2 2.5kJ beams; NIF with 3 kJ, and beamlet at Sandia National Laboratory, Albuquerque. These facilities are aimed in part at achieving gain 0.1 and investigating the 1-10 keV material temperature regime.

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