EXECUTIVE SUMMARY

The Fusion Science Center (FSC) for Extreme States of Matter and Fast Ignition (FI) Physics began operation in August 2004 under the sponsorship of the Department of Energy (DOE), the Laboratory for Laser Energetics (LLE), the University of Rochester (UR) and the Institute for Laser Science Applications (ILSA) at Lawrence Livermore National Laboratory. In FY06, $150K in matching funds were provided by the New York State Energy Research and Development Authority (NYSERDA) through LLE, UR contributed with $81K of indirect-cost waivers, and the DOE provided $1.088M under cooperative agreement DE-FC03-ER54789. Ten institutions and ten principal investigators participate in the FSC. The FSC is aimed at fostering close collaboration among the Center investigators with the ultimate goal of successfully integrating compression and FI-heating experiments. A major goal of the Center is to bring together researchers from around the country and the international community to build a comprehensive understanding of the physics underlying the creation of extreme states of matter and fast ignition. Another major function of the Center is to stimulate academic involvement and student interest in the area of High Energy-Density Physics (HEDP). As part of its outreach and academic mission, the FSC has organized the 9th International Fast Ignition Workshop (2006) and has planned the 2007 Summer School in High Energy Density Physics.

FSC Outreach and Education Mission

The FSC has planned its second summer school in High Energy Density Physics for the week of July 29-August 4, 2007, in La Jolla (CA). The summer school will be held on the Campus of the University of California San Diego. The FSC will provide approximately fifty scholarships to graduate and undergraduate students. Fourteen scientists from the field of High Energy Density Physics will lecture on a broad range of subjects including: laser-plasma interactions, laboratory astrophysics, equations of state, plasma-based particle accelerators, inertial confinement fusion, high-energy lasers, Z-pinches, material science under extreme conditions, and HEDP diagnostics. Student and participant posters will accompany each day’s thematic focus. Daily poster sessions offer the students a unique opportunity to discuss their work in detail, not only with the lecturers but with the many other students who are in attendance. As part of its outreach activities, the FSC sponsored and organized the 9th International Fast Ignition Workshop on November 3-5, 2006, in Cambridge, MA. In attendance at the FI workshop were 94 scientists from 8 countries giving 66 presentations including 21 invited talks. More detailed information concerning the 2007 HEDP Summer School and the 2006 Fast Ignition Workshop are available on the FSC web site at http://fsc.lle.rochester.edu/.
Progress in Fast-Ignition Research

The FSC has promoted close collaboration among several HEDP researchers (some supported by the Center and some by other sources) in the area of laser-plasma interactions, electron transport, hydrodynamics and target fabrication, with the main focus of these disciplines centered on fast-ignition inertial confinement fusion.

The FSC identified the following fundamental areas critical to the success of Fast Ignition:

[1] Fuel Assembly

Progress in Fast-Ignition Fuel Assembly (Theory/Experiments).

Fuel Assembly for Fast Ignition (Theory) (UR). The implosion hydrodynamic theory for fast-ignition fuel assembly was developed by the FSC in the previous budget period [R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005)]. In 2006, a set of massive cryogenic wetted-foam targets were designed and optimized for direct-drive Fast Ignition [R. Betti et al, Plasma Phys. Cont. Fus. 48, B153 (2006)]. Such targets are driven on a very low adiabat and low velocity to produce dense cores with high densities and areal densities, and small hot spots. Such slowly assembled massive targets have low in-flight aspect ratios (IFAR ≈ 16), shaped adiabats, and large thicknesses. These characteristics make these targets insensitive to the hydrodynamic instabilities during the acceleration phase. The gain curves attainable from such fuel assemblies are derived [R. Betti et al, Phys. Plasmas 13, 100703 (2006)] based on one-dimensional simulations of the implosion, and two-dimensional simulations of ignition by a collimated electron beam and burn propagation. The FI targets are designed for a UV laser driver with energy ranging from 25 kJ to 2 MJ. Since the implosion characteristics are set by the optimized target design, the ratio of the thermonuclear energy to the compression laser energy is a unique function of the driver energy on target. It is shown that, if ignited, the fuel assembled by a 100-kJ UV laser can yield close to 6 MJ of thermonuclear energy.

Fuel Assembly for Fast Ignition (Experiments) (UR, MIT). A set of plastic targets and pulse shapes have been designed and imploded on OMEGA to test the ability of slow, low-adiabat implosions to achieve the high densities and large areal densities required for fast ignition [C. Zhou et al, Phys. Rev. Lett. 98, 025004 (2007)]. Massive 40µm-thick plastic shells filled with 25-35 atm of D₂ or D³He were imploded on a low-adiabat (α≈1.3) and with a low-implosion velocity (~2•10⁷ cm/s) on the OMEGA laser to generate massive cores of compressed plasma with high areal densities optimal for fast ignition. The targets are driven by relaxation (RX) adiabat-shaping laser pulses to keep the inner portion of the shell near Fermi-degenerate. The RX laser pulses have 20 kJ of UV laser energy and are characterized by an 80-ps picket followed by a 2.5-ns shaped main-pulse. The areal densities of the compressed core are inferred from the downshift of
the secondary (for D² filled targets) and the primary (for D³He filled targets) fusion proton spectra. The measured kinetic energy downshift of the proton spectra is in good agreement with the theoretical predictions yielding burn-averaged areal densities of \(0.130 \pm 0.017 \text{ g/cm}^2\) and peak \(\rho R\) during the burn of about \(0.24\pm 0.018 \text{ g/cm}^2\), the largest \(\rho R\) measured on OMEGA to date. The same implosions with empty CH shells are expected to reach \(1.3 \text{ g/cm}^2\) across the core (i.e. \(2\rho R\)) enough to stop hot electrons with energies up to 4.5 MeV typical of fast ignition scenarios.

**Progress in Hot-Electron Transport and Intense LPI Experiments**

**Benchmarking Experiments for Electron Transport (UCSD, GA, OSU).** The goal of this work is to design and field experiments to directly test components of the modeling codes used to design fast ignition experiments. We focus on two critical areas: electron transport and laser-plasma interaction. Until now, the modeling for those components has been descriptive, containing enough heuristically determined free parameters that the experimental results cannot be used to validate the codes. In 2006, we have performed fundamental experiments on electron transport to benchmark against three numerical codes, namely e-PLAS, PICLS and LSP. The results are encouraging with the key differences in electron transport between the three different codes having been identified. In addition, we have performed the first experiment to study electron transport in shock heated targets, which will be repeated on a larger scale when OMEGA-EP becomes available. Shots onto nail targets, a new configuration for electron transport experiments designed to benchmark numerical codes, have been performed. These targets have been used in campaigns at the Vulcan and Titan laser facilities during the Fall 2006. Three geometries were used—100 µm diameter head on a 20 µm diameter copper wire, headless 50 µm diameter titanium wire, and cone-wire targets with a 20 µm diameter copper wire. The main diagnostics included imaging of XUV emission at 68 eV and 256 eV, \(K_{\alpha}\) imaging at 8.0 keV (Cu \(K_{\alpha}\)) and at 4.5 keV (Ti \(K_{\alpha}\)). Initial analysis shows that much of the laser energy was converted into hot electrons, a large fraction of which were confined to the head. There was an exponential fall-off in energy deposition with a 1/e length \(\sim 150\) µm. In contrast, in the case of the cone-wires, \(K_{\alpha}\) emission was observed all the way down the wire (1 mm length) though the exponential fall off in x-ray emission was similar. The hot electrons in the head are primarily confined due to the magnetic field whereas in the cone-wire case, the hot electrons are guided along the surface by the surface electric and magnetic fields. The currents generated in both cases exceed the Alfvén limiting current thus requiring a neutralizing return current.

**Hot-Electron Production from Intense Irradiation of Nanometer-Scale Sphere Targets (UT).** Hot-electron generation experiments have been carried out from novel nanoscale targets on the THOR laser at the University of Texas at Austin. In particular, we have investigated hot-electron generation and x-ray production from targets coated with microspheres. This work is motivated by the possibility that spheres with size comparable to the wavelength of the incident laser radiation can result in electric field enhancements through well known Mie resonances. This local field enhancement could then lead to more efficient electron generation and brighter x-ray production. During the
past year, we have investigated hard x-ray (>10 keV) generation from fused silica targets coated with a monolayer of monodisperse polystyrene spheres of size comparable to the laser wavelength. X-ray yields at two photon energies as a function of sphere size are measured, and a clear peak in the x-ray yield for spheres with size 260 nm diameter is observed. The data appear to provide strong evidence of the importance of Mie resonant field enhancement in the production of hot electrons at these intensities (which are sub relativistic).

**Electromagnetic Field Measurements in the Compressed Cores of FI Targets (MIT)**

The goal of these experiments is to study the EM fields in cone-in-shell capsules and to predict the effects of such fields on the hot-electron transport to the dense core. The specific experiments were designed to (a) study E and B fields in implosions of spherical capsules driven symmetrically; (b) study E and B fields in implosions of spherical capsules with the asymmetric drive used for cone-in-shell capsules; (c) study E and B fields in cone-in-shell capsule implosions; (d) study the interactions of a ring of 6 laser beams with a planar CH foil, with and without a cylinder of Au inside the ring as surrogate for the Au cone in cone-in-shell capsules. A full day of OMEGA shots was assigned to this campaign on 14 February 2007. The E and B fields are measured through proton deflectometry. The proton source, or backlighter, is a glass, D3He-filled capsule imploded using a small subset of the OMEGA laser beams. The emission of 15-MeV D3He fusion protons is isotropic and monoenergetic. Such monoenergetic sources have distinct advantages over broad-band proton sources associated with intense-laser-beam experiments. The imaging detector is CR-39, a nuclear track detector with high spatial resolution, energy resolution, and low sensitivity to electromagnetic and x-ray noise. For each experiment, the object to be imaged was placed between the proton source and the detector to allow capture of a magnified image of the object. The analysis of the experimental data from the February experiments is currently under way and will be reported at the next APS-DPP meeting.

**Progress in Integrated Fast-Ignition Simulations and Code Development**

**2D PIC Simulations of Channeling in Underdense Plasma (UR).** In 2006, 2D PIC simulations were performed with the code OSIRIS showing that channeling in mm-scale plasmas is a highly nonlinear and stochastic process involving pulse self-focusing and filamentation, transverse channel expansion through shock waves, longitudinal plasma piling-up, pulse-hosing and channel bifurcation, and channel self-correction. At \( I=10^{19} \) W/cm\(^2\), the channel residue plasma density is \( \sim 0.05n_c \), and it takes tens to a hundred picoseconds, not a few picoseconds as predicted by the linear theory, for the channeling pulse to propagate through the mm-long underdense region. In our 2D PIC simulations, a channeling pulse of wavelength \( \lambda_0=1 \) µm is launched from the left boundary of the simulation box with peak intensities of \( I=10^{18-19} \) W/cm\(^2\) and a rise time of 495 fs, after which the pulse amplitude is kept constant. It is found that the channel propagation velocity \( v \) is stochastic but generally \( v/c>0.1 \) for \( I=10^{19} \) W/cm\(^2\). For \( I=10^{18} \) W/cm\(^2\), preliminary analysis shows that the residue density does not change significantly but the advance speed is much lower, \( v/c\sim 0.02 \). These results have been presented at the 2006
Fast Ignition Workshop, the 2006 and 2007 FSC meetings, and will be submitted for publication in ’07.

2D PIC Integrated Simulations of Fast Ignition with OSIRIS (UCLA). A variety of improvements have been made in 2006, extending the modeling capabilities of OSIRIS. These include improved particle collisions and absorbing boundary conditions for the fields. The latter allow for the implementation of absorbing boundaries in more than one direction. A particle collision package has been added for use with fast ignition simulations parameters. Since fast ignition is critically dependent on the amount of energy that can be transmitted from the critical surface to the dense (~300 g/cm$^3$) core, our simulations seek to determine how much energy is transmitted into the dense core and how we can increase the amount of energy deposited into the dense core in non-cone targets. The energy spectrum of the electrons reaching the dense core is as important as the total energy carried by these electrons. If the energy of the individual electrons is too high, they will pass through the core without collisionally heating it. In our model, no cone is used to attempt to focus the electrons. We use large scale PIC simulations to model the fast ignition target. We consider isolated targets to prevent the boundary conditions from affecting the simulation results. In the most recent simulations, we model a 50 µm radius target at 100 times the critical density. The energy spectrum is computed for those electrons reaching the core. Lower energy electrons (~1 MeV) deposit their energy in the core much more efficiently than higher energy electrons that go through the core without significantly slowing down. The hot-electron spectrum deduced from our large simulations shows that the electron energy is reduced to about ~1 MeV in correspondence of the dense core. This is a very favorable result for fast ignition, and is in contrast with the prediction of the ponderomotive scaling formula that yields extremely high electron energy and poor coupling efficiency.

2D PIC Integrated Simulations of Cone-Guided Fast Ignition with PICLS (UNR) Simulations of the high-intensity, short-pulse interaction with cone-guided fast ignition targets are carried out with the 2D collisional PIC code PICLS. Such simulations include the relevant physics self-consistently including the hot-electron generation, fast ion acceleration, energy transport in large density scale coronal plasmas, and energy coupling in the core including collisional processes. We found that electromagnetic instabilities develop around the cone target where the plasma density is less than a few hundred times the critical density. No significant fields have been detected near the core area, thus indicating that the core heating is mainly due to collisional processes. The dominant core heating mechanism was identified as the drag heating between hot and bulk electrons in the simulation. We also found that the hot-electron temperature observed in the simulation is lower than predicted by the ponderomotive scaling, after the pre-plasma inside the cone was blown away by the strong photon pressure. A novel fast-ignition relevant hot-electron temperature scaling is obtained, and compared with the simulation results. This scaling can be used to determine the input hot-electron temperature in hybrid simulations. This work has been submitted for publication in Physical Review Letters in 2007.
Progress in Shock Ignition of Thermonuclear Fuel with High Areal Density.

Theory of Shock Ignition (UR). Shock ignition is a novel method to assemble and ignite thermonuclear fuel. Massive cryogenic shells are first imploded by direct laser light with a low implosion velocity and on a low adiabat leading to fuel assemblies with large areal densities. The assembled fuel is ignited from a central hot spot heated by the collision of a spherically convergent ignitor shock and the return shock. The resulting fuel assembly features a hot spot pressure greater than the surrounding dense fuel pressure. Such a non-isobaric assembly requires a lower energy threshold for ignition than the conventional isobaric one. The ignitor shock can be launched by a spike in the laser power or by particle beams. The thermonuclear gain can be significantly larger than in conventional isobaric ignition for equal driver energy. The theory of non-isobaric shock ignition and 1D/2D simulations of shock ignited implosions are described in a paper that will appear in Physical Review Letters in 2007.

Experiments on Shock Ignition (UR). Surrogate plastic shell implosion experiments have been designed and fielded on the OMEGA laser system on January 10, 2007. The targets have the same characteristics of fast ignition targets. Massive plastic shells with a 40-µm thickness and 430-µm outer radius, filled with 18-atm and 25-atm D₂ gas are imploded on a low adiabat $\alpha \approx 1$-1.5 by a 17-19 kJ OMEGA relaxation-type laser pulse. Two kinds of pulse shapes have been used: (a) conventional shaped pulses, and (b) pulse shapes with a power spike designed to drive a spherically convergent shock. The power spike occurs at the end of the pulse and resembles the shock-ignition pulse shapes. Up to a four-fold increase in the neutron yield is measured for the shock-ignition pulse shapes. The areal densities inferred from the downshift of the secondary proton spectrum also showed an improvement in compression for shock-ignition pulse shapes. A second shock-ignition experimental campaign is scheduled for April '07.
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THE FUSION SCIENCE CENTER
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R. Town (LLNL)

Member is a Researcher (post doc or scientist) partially or fully supported by the FSC, or a Principal Investigator. Graduate students are fully or partially funded by the FSC, or closely collaborating with the FSC. Collaborators are not currently supported by the FSC.
REFEREED PUBLICATIONS
(Published or submitted for publication in 2006)

[1] Shock ignition of thermonuclear fuel with high areal density

[2] Hydrodynamic relations for direct-drive and fast-ignition inertial confinement fusion
C. D. Zhou and R. Betti, (submitted to) Physics of Plasmas


[4] Bubble acceleration in the ablative Rayleigh-Taylor instability

[5] Progress in hydrodynamic theory and experiments for direct-drive and fast ignition inertial confinement fusion

[6] Gain curves for direct-drive fast ignition at densities around 300 g/cc

[7] Low-adiabat implosions for fast-ignition inertial confinement fusion

[8] Overview of recent progress in US fast ignition research

[9] Comparison of solid and plasma linear energy deposition for electron preheat and fast ignition


[12] Space-Charge Effects in the Current-Filamentation or Weibel Instability,

[13] A global simulation for laser-driven MeV electrons in 50-µm-diameter fast ignition targets,

[14] Development of an in situ peak intensity measurement method for ultraintense single shot laser-plasma experiments at the Sandia Z-Petawatt facility,


[16] Status of and prospects for the fast ignition inertial fusion concept,

[17] High energy electron transport in solids

[18] Temperature sensitivity of Cu Kα imaging efficiency using a spherical Bragg reflecting crystal

[19] Study of electron and proton isochoric heating for Fast Ignition
INVITED PRESENTATIONS AT CONFERENCES

[1] Progress in hydrodynamic theory and experiments in direct-drive and fast ignition inertial confinement fusion,
   R. Betti

[2] Gain curves for fast ignition inertial confinement fusion
   A. Solodov

   R. Rygg

[4] Monoenergetic proton backlighter for measuring E and B fields and for radiographing implosions and high-energy density plasmas,
   CK. Li

[5] PIC simulation of fast ignition targets
   J. Tonge,

[6] Electron transport in wire targets
   F. N. Beg et al.,

[7] Fast ignition research at the Laboratory for Laser Energetics
   W. Theobald et al.,

[8] A review of fast ignition
   M.H. Key

FUSION SCIENCE CENTER MEETINGS

3rd Fusion Science Center Meeting, January 26-27 (2006), Rochester NY

4th Fusion Science Center Meeting, August 28-29 (2006), Livermore CA

(FSC meeting presentations are available on the FSC web site at fsc.lle.rochester.edu)
THE FSC EDUCATION MISSION

The 2nd FSC Summer School in High Energy Density Physics
July 29-August 4, 2007 UCSD Campus, La Jolla CA

Scheduled lecturers and subjects
C. Back–GA, Material Science and ICF
R. Betti–UR, Implosion Hydrodynamics
M. Campbell–GA, Fusion Energy
T. Ditmire – UT, HEDP
R. Freeman –OSU, Fast-Electron Transport
D. Hammer – Cornell U, HEDP with Z-Pinches
C. Joshi – UCLA, Plasma Accelerators
M. Key – LLNL, Fast Ignition
M. Marinak –LLNL, Hydrodynamic Simulations
D. Meyerhofer– UR, HEDP Diagnostics
W. Mori – UCLA, Laser-Plasma Interaction
E. Moses – LLNL, National Ignition Facility
B. Remington- LLNL, Introduction to HEDP
M. Rosen, LLNL, Inertial Confinement Fusion

50 financial aid packages. Sponsors: FSC and ILSA
THE FSC OUTREACH

The 9th International Fast Ignition Workshop
Organized by the FSC
November 3-5, 2006, Cambridge MA, USA

→ 94 attendees from 8 countries
→ 66 presentations available on the FSC web site
ELECTRON TRANSPORT EXPERIMENTS

A. Short-Pulse Experiments in Nail, Wire, Cone-Wire and Shock-Heated Targets (UCSD/GA/OSU/LLNL)

The goal of this work is to design and field experiments to directly test components of the modeling codes used to design integrated Fast Ignition experiments. We focus on two critical areas: electron transport and laser-plasma interaction. Until now, the modeling for those components has been descriptive since they contain enough heuristically determined free parameters that the experimental results cannot be used to validate the codes. In 2006, we have performed fundamental experiments on electron transport to benchmark against three numerical codes namely, e-PLAS, PICLS and LSP. The results are encouraging with the key differences in electron transport between the three different codes having been identified. In addition, we have performed the first experiments to study electron transport in shock heated targets, which will be repeated on a larger scale when OMEGA-EP becomes available.

Nail, Wire and Cone-Wire Targets. Nail targets, a new configuration for electron transport experiments, were designed for code-benchmarking experiments. These targets (Fig. 1) have been used in campaigns at the Vulcan and Titan laser facilities during the Fall of 2006. Three geometries were used—100 µm diameter head on a 20 µm diameter copper wire, headless 50 µm diameter titanium wire, and cone-wire targets with a 20 µm diameter copper wire. The main diagnostics included imaging of XUV emission at 68 eV and 256 eV, K\textalpha imaging at 8.0 keV (Cu-K\textalpha) and at 4.5 keV (Ti-K\textalpha).

![Diagram of target configurations](image)

Figure 1. Three types of targets were used: (a) the nail target: 100 µm head with a 20 µm diameter copper wire, (b) 50 µm titanium wire and (c) cone-wire with a 20 µm diameter wire. The length of the wire in all three cases was 0.7-1 mm.
Images shown in Fig. 2 are from experiments performed with the Vulcan Petawatt laser with an intensity of \( \sim 2 \times 10^{20} \) Wcm\(^{-2}\) (laser energy \( \sim 500 \) J, pulse length \( \sim 0.5 \) – 1 ps). Initial analysis shows that much of the laser energy was converted into hot electrons, a large fraction of which were confined to the head. There was an exponential fall-off in energy deposition with a 1/e length \( \sim 150 \) µm. In contrast, in the case of the cone-wires, \( K_\alpha \) emission was observed all the way down the wire (1-mm length) though the exponential fall-off in x-ray emission was similar (Fig. 2). The hot electrons in the head are primarily confined due to the magnetic field whereas in the cone-wire case, the hot electrons are guided along the surface by the surface electric and magnetic fields. The currents generated in both cases exceed the Alfvén limiting current. Therefore, there has to be a return current for the hot electrons to propagate down the wires. In the case of the nail targets, the return current is provided by the cold electrons moving from ground. In the case of the cone-wire, this current is provided by refluxing hot electrons from the end of the wire.

In addition, experiments were performed on wires using the Titan laser (Intensity \( \sim 6 \times 10^{19} \) Wcm\(^{-2}\), pulse length \( \sim 0.5 \) ps) at the Lawrence Livermore National Laboratory. The primary motivation was to study the hot-electron transport without the effect of the head. In these experiments, 50 µm diameter titanium wires were used, to provide a suitably large target given the pointing accuracy of the laser. Figure 3 shows a titanium \( K_\alpha \) image of such a target. The x-ray decay length is longer than in the nail targets. The hot-electron heating on the surface of the wire is evident even after the 90° bend as shown in the line out in Fig. 3(b). The strong electric and magnetic fields are guiding the hot electrons around the 90° bend.
The XUV measurements showed different behavior between the nail and cone-wire targets. XUV emission from the nail targets was observed to extend beyond 1 mm (Fig. 4). Hydrodynamic jets were seen to emanate from the convex surfaces of the target. Interestingly, XUV emission was observed only from the aluminum cone, over an area much larger than the laser spot. There was no emission from the wire attached to the cone. This raises an interesting question about the high intensity laser interaction with the cone, which is not well understood. Is this plasma created by the prepulse? If this is the case, then, when the main laser pulse arrives, it interacts with the plasma formed by this prepulse. This will be investigated in future experiments. These observations clearly indicate that the wire is heated by the return current from the ground in the case of the nail targets. In the cone-wire case, the return current is provided by the refluxing electrons from the end of the wire, evidence of which is clear in the K$_\alpha$ images.

Figure 3. (a) K$_\alpha$ radiograph of the self emission from a 50 $\mu$m diameter titanium wire. X-ray emission can be seen at the surface after 90° bend as shown in the line out (b).

Figure 4. XUV images at 68 eV for the (a) nail target and (b) cone wire target. No emission can be seen from the wire in the case of the cone-wire target.
**Shock-Heated Targets.** A major goal of this work is to study hot-electron transport in warm dense matter (WDM) in conditions similar to those of the plasma surrounding a compressed fuel core in a re-entrant cone-guided fast ignition target. It is also important to study the effect of the prepulse driven shock traveling into the tip of the cone and consequent effects upon hot-electron transport. We designed a shock-heated foam experiment that was fielded on Titan to study electron transport in such WDM. A 300 J, 2 ns, 532 nm drive pulse accelerates an Al/Cu flyer plate to compress the initially 100 mg/cc foam to > 1 g/cm$^3$. The shock heats the foam to ~30 eV and is partially reflected from a gold layer on the far side. The scenario bears some similarity to the re-entrant cone tip as it faces the stagnating core. A short pulse incident upon the far side of the gold layer then injects electrons through the gold, the shock front, and into the hot plasma. The hot electrons are counted by the Cu-K$\alpha$ fluorescence when they hit the Al/Cu flyer plate. The K$\alpha$ fluorescence data, which takes the form of single hit photon counting, HOPG spectroscopy, and K$\alpha$ imaging, is then compared to similar measurements made without hot plasma between the gold and copper. Two such reference measurements are made 1) with a solid density cold CH slab of similar areal density to the compressed foam in place of the shock compressed foam, and 2) with the Au in direct contact with the Cu pusher plate. The data analysis is currently underway.

**Experiments on the 100TW Sandia Laser Facility.** The Fusion Science Center has carried out experiments at Sandia National Laboratory in 2006. The SNL 100-TW laser facility is still in the commissioning phase. We plan to perform Fast Ignition related experiments in 2007-08. Recently, a series of 19 shots on the 100 TW facility at Sandia National Laboratory was completed to quantify the pointing stability, K$\alpha$ spot size and pre-pulse effects of the Z-Petawatt laser. The configuration, as shown in the plan view of Fig. 5, consisted of a 25-µm thick Cu foil at target chamber center situated with its normal at 45° to the incident 1053-nm, ~21-J, ~3-ps short pulse laser. This probe beam was compressed separately from, and delayed 0 – 240 ps relative to, the 3-ps interaction pulse, to provide a 300-fs back light. An off-axis spherical Bragg crystal imager at 45° to the target surface normal provided a 7x magnified, ~15-µm resolution rear view of Cu-K$\alpha$ emission. The resulting images, recorded using Fujifilm BAS-SR image plates, were used to provide information on shot-to-shot variations in K$\alpha$ spot intensity and position. The Cu-K$\alpha$ images show an average spot diameter of ~71±11µm and a pointing error of ≤50 µm in both vertical and horizontal directions. Also, very good S/N results ranging from 30 to 140 were obtained. Figure 6 shows an example Cu-K$\alpha$ image. In the image, the flux of electrons throughout the foil is apparently sufficient to illuminate the whole foil. A series of radiochromic

Figure 5. Plan view of laser/diagnostic configuration within the Z-PW chamber

Figure 6. K$\alpha$ image of a 25µm Cu foil viewed at 45° to the foil normal. FWHM spot size is 65µm.
film (RCF) packs were placed at 2-3 cm from the rear surface of the target. These packs were used to characterize the energies of protons emitted from the rear surface. These stacks showed an average peak proton energy of 7.7±2.4 MeV.

**Benchmarking Nail and Wire Target Experiments.** High intensity short pulse laser produced relativistic electron-beam propagation in the novel “nail” and wire targets has been modeled using three codes: PICLS, which is an explicit PIC code, and the implicit/hybrid PIC codes, e-Plas and LSP. The motivation for these simulations is to benchmark the codes against the experimental data. The low mass “nail” and wire targets are excellent for this purpose as most of the laser and target parameters can be incorporated into the simulations. Laser solid-target interaction, hot-electron generation and propagation in the wire targets are self-consistently modeled by the explicit 2D PIC code PICLS which includes fully relativistic e-e, e-ion and ion-ion collisions. The ionization degree is fixed at Z=15 for the Cu nail target with electron density of 6×10^{23}\ cm^{-3}. Titan laser parameters are used in this simulation, i.e., \( I=6.4 \times 10^{19} \ \text{W/cm}^2 \) with a pulse length of 500 fs (Gaussian profile) and a focal spot size of 20 \( \mu \)m (also Gaussian). To mimic the ASE produced preformed plasma, a pre-plasma with a scale length of 5 \( \mu \)m and a density of \( 10^{20} - 10^{22} \ cm^{-3} \) is located on top of the solid “nail” target. PICLS simulations of a 350 \( \mu \)m long nail target have been carried out over a time interval of 2 ps, allowing much of the physics of the real target to be captured. The e-PLAS code is a 2D hybrid code which treats hot electrons as particles and the background plasma as a fluid. Momentum equations are solved implicitly. Scattering and drag of the hot electrons against the background fluid and the scatter of the cold electrons off the ions is done at the Spitzer rate with a temperature capped at, typically, 100 eV. The hot drag and scattering rates are relativistically corrected. In simulations of the Cu nail targets, a beam of hot electrons with a relativistic Maxwellian momentum distribution is emitted from the critical surface for interaction with a 1\( \omega \) laser (1.7 \times 10^{20} \ \text{W/cm}^2 \) for 1 ps: Vulcan PW laser parameters). The ionization level is fixed at Z=15 and the wires are 200 \( \mu \)m in length. Simulations using the Titan laser parameters with longer wires are currently underway. Electron beam propagation in the long nail and wire targets has also been modeled using the hybrid PIC code, LSP, which also uses an implicit algorithm, but with a direct approach. Classic Spitzer collision rates are used. Hot-electron beams can either be promoted from the background cold electrons using the ponderomotive scaling or directly from the interaction of the high intensity laser with the solid targets. Both creation methods have been tested and employed. In the latter, a short laser pulse is launched from a boundary and interacts with a preformed plasma with a scale-length of 15 \( \mu \)m and particle density of \( 10^{20} - 10^{22} \ cm^{-3} \). Electrons in this preformed plasma are treated as kinetic particles. In all these simulations, a preformed plasma in front of the solid “nail” and wire head is included. Such preformed plasma is produced from the interaction of the ~ nanosecond long ASE prepulse of a CPA laser with the solid target before the arrival of the main pulse. 2D radiation hydrodynamics simulations have suggested that such prepulse significantly modify the shape of the “nail” and wire head. This may have important effects on the laser absorption, hot-electron generation and propagation. Simulation results so far have shown reasonable agreement among the codes as well as in comparison with the experiments. One striking feature is that most hot electrons remain in the nail head as indicated in Fig. 7, showing the hot-electron density or electron energy density plots from the three codes. Within less than 15 \( \mu \)m from the interaction region, hot-electron density has the sharpest decrease. Generally, the hot-electron number density drops from a few times \( 10^{21} \ cm^{-3} \) to \( 10^{20} \ cm^{-3} \) over a length of 100 \( \mu \)m along the wire. This is roughly consistent with the experimental results inferred from the Cu K\( \alpha \) imager shown before. The nail head is found to be heated up to \( \sim 1.7 \) keV in e-PLAS and around 1 keV in LSP, but significantly higher (> 10 keV) in PICLS. The second prominent feature observed in all three simulations, particularly in the PICLS simulations, is a small component of surface current that develops a much larger decay length than the rest of the
hot-electron population. This leads to surface heating, as shown in Figure 8. Figure 7 comprises an energy density plot from PICLS and background electron temperature plots taken from LSP and e-PLAS simulations. The amount of surface heating has been found to be sensitive to the details of the heating sources included in the models. For example, in the e-PLAS code with collisions set to zero, more current is found to flow along the surface. Nevertheless, all the simulation results predict the long-range surface current and the corresponding thermal emission as observed in the experiments. The third pronounced feature in the simulations is the prediction of strong electric and magnetic fields. Figure 9 shows the azimuthal magnetic fields produced in the e-PLAS and LSP simulations after 1 ps. At the laser plasma interaction region, magnetic fields with a magnitude of 100 MG can be seen. This B field has been found to confine the hot electrons near the “nail” head. On the wire surface, strong magnetic and radial electric fields (~MV/µm, not shown here) co-exist, spatially slightly separated. Hot electrons are confined by these two fields and flow along the surface.

Figure 7: Simulations show energy concentration near the interaction region. a) hot electron density plot at 0.94 ps in e-PLAS; b) energy density plot at 1.5 ps in PICLS; and c) hot electron density plot at 2.3 ps in LSP.
In conclusion, strong similarities of the electron beam transport and heating of the background plasma have been found in the simulations using the three available codes, although with some recognizable quantitative differences that may be caused by the details of the collision models and initial temperatures employed. We are currently extending the simulations to later times with longer nails and wires. This may be needed for benchmarking purposes as energy transfer from hot electrons to the cold background plasma takes a much longer time, > 10 ps as measured in COMET experiments performed by Chen et al., at LLNL, than has been covered by the simulations performed to date. Meanwhile, working through the differences between experiments and simulations will provide us with the needed guidance to refine the computational tools and correctly simulate the experiments. This in turn aids our physical understanding of these experiments and related scenarios of direct relevance to fast ignition.
B. Magnetic and Electric Fields in Fast Ignition Fuel Assemblies (MIT)

Among the many important and complex processes involved in Fast Ignition (FI) are the assembly of a high-density (~ 300g/cc) DT plasma and then the rapid deposition of energy (from directed electrons or possibly protons), which ignites the assembled fuel. Though there are many complicated features of this problem, some of which are being addressed by other institutions and task forces within the FSC, MIT has focused on the diagnostics of the areal density, and electric and magnetic fields in and around the target that might affect the transport of the hot electrons.

Monoenergetic Proton Radiography of Laser-Plasma Interactions and Capsule Implosions. The compression and assembly of fuel near the cone tip, and the magnitude and distribution of electromagnetic fields generated around the Au cone are two active areas of investigation. To sensitively and simultaneously probe the matter and field distributions, MIT has developed a novel monoenergetic proton source, and a matched, high-quality detection system, for proton radiography. A large quantity of data was acquired in a series of shots at OMEGA on 14 February 2007, and a brief introduction is given here for a small fraction of the data which have undergone preliminary processing. The idea was to study the characteristics of imploding cone-in-shell capsules by themselves, to contrast them with imploding spherical capsules, and to study separate issues that make these types of implosions different from each other. The specific experiments were designed to (a) study E and B fields in implosions of spherical capsules driven symmetrically; (b) study E and B fields in implosions of spherical capsules with the asymmetric drive used for cone-in-shell capsules; (c) study E and B fields in cone-in-shell capsule implosions; (d & e) study the interactions of a ring of 6 laser beams with a planar CH foil, with and without a cylinder of Au inside the ring as surrogate for the Au cone in cone-in-shell capsules; (f) Improve understanding of laser-matter interactions with simultaneous front- and back- side imaging.

Schematics of the setups for these experiments are shown in Figure 10. The proton source, or backlighter, is a glass, D₃He-filled capsule imploded using a small subset of the OMEGA laser beams. The emission of 15-MeV D₃He fusion protons is isotropic and monoenergetic. Such monoenergetic sources have distinct advantages over broad-band proton sources associated with intense-laser-beam experiments. The imaging detector is CR-39, a nuclear track detector with high spatial resolution, energy resolution, and low sensitivity to electromagnetic and x-ray noise. For each experiment, the object to be imaged was placed between the proton source and the detector to allow capture of a magnified image of the object. In the case of experiments (d) through (f), where it was desired to precisely measure the field distribution generated by the interaction of laser beams with planar foils, a Ni mesh was used to break up the proton source into beamlets, which can be used to map the field structure through deflectometry. To simultaneously measure fields and areal density in ICF targets for experiments (a) through (c), the mesh was removed and the foil was replaced with a target capsule (unimploded or imploded). Field structure is then studied using the spatial distribution of proton fluence, and areal density is studied through the dependence of proton energy on spatial position (proton paths that probe higher areal densities will result in greater energy downshift, and lower energies on the detector).
Figure 10. The proton radiography setup for 14 February 2007 fast-ignition experiments. A backlighter capsule filled with D³He fuel is imploded with a small subset of the OMEGA drive beams, which results in isotropic emission of 15-MeV protons. CR-39 detectors were used to capture the radiographic images of (a) symmetrically- and (b) asymmetrically-driven spherical capsule implosions, (c) cone-in-shell capsule implosions at various times, as well as a 6-beam ring of lasers incident on planar CH foils either (d) without or (e) with a Au cylinder attached to the center, and finally (f) the simultaneous interaction of beams on either side of a CH foil. A Ni mesh is used to break up the protons into beamlets for planar foil images.
All experiments were performed, but so far only the primary (not secondary) detectors from experiments (10c) through (10e) have been processed (each detector must be etched in NaOH and scanned and processed on a special MIT-developed microscope system). Preliminary results of experiments (10d) and (10e), the proton radiography of fields generated by 6 laser beams on a CH foil with and without a 500-µm-diameter Au tube, are shown in Figure 11. Quantitative analyses of these data have just begun, and will include field analysis based on the techniques described in Li et al., “Magnetic reconnection in laser-produced, high-energy-density plasmas” (to be submitted to Nature, 2007), and F. H. Séguin et al., “Proton radiography options for OMEGA EP” (to be submitted, 2007).

![Figure 11. 15-MeV proton radiographs of the magnetic field structure generated by the interaction of a ring of 6 laser beams with a CH foil with (a-c) and without (d-e) a small gold tube, recorded at different times with respect to the onset of the laser pulse. For fast ignition, it is crucial to understand the effects of laser-generated fields upon the transport of the igniting electron or proton beam. These experiments bear directly on such issues.](image)

Preliminary results of experiment (10c), proton radiography of unimploded and imploded cone-in-shell targets, are shown in Figure 12. In order to avoid having protons produced in the imploded capsules confused with those protons used to generate the radiographs, the imploded capsules were filled with air. Because of the scattering and ranging of protons through the Au cone, radiographs were only taken perpendicular to the cone axis. (The experiments described above with a gold tube on a CH foil give some flavor for the fields generated around the cone axis.) A preshot visible-light image of the target can be seen in Figure 12(a), where the capsule sphere is 860 µm in diameter. The
remaining 15-MeV proton radiography images are of an unimploded target and an imploded target at 1.5 ns after the onset of 36 of OMEGA’s 60 beams on the target sphere.

Figure 12. Images of a spherical CH capsule with inserted Au cone, before and during implosion at OMEGA, using visible light (a) and 15-MeV protons (b-e). Images (a), (b), and (c) show the unimploded capsule used in shot 46531. Images (d) and (e) show a capsule similar to that of (a) but at 1.5 ns after the onset of a laser pulse that imploded it with 14.1 kJ of laser energy using 36 of OMEGA’s 60 beams (shot 46529). These experiments are directly relevant to fast ignition.
Each radiograph contains both spatial information and energy information, because the CR-39 detectors record the position and energy of every individual proton. Each radiograph can thus be displayed in several different ways, and in Fig. 12 they are shown as fluence versus position and mean proton energy versus position. The dark areas of (12b) and (12d) correspond to regions of greater proton fluence, whereas the dark areas of (12c) and (12e) correspond to regions of lower mean proton energy. The downshift in proton energy (from the incident energy of 15 MeV) is proportional to the amount of matter traversed between the source and detector. Many interesting and important features are immediately evident in these images. The radial compression of the capsule itself during the implosion is clear. The angle subtended by the cone shadow increased from 34° to ~100° by 1.5 ns, as a substantial Au plasma is blown off of the cone by the edges of the laser beams. In addition, fascinating and complex filamentary structures in the ablating coronal plasma can be seen in the proton fluence image (12d) but not in the energy image (12e). Importantly, that means that the fluence variations must be due to spatially varying focusing of the backlighter protons, as they pass through the corona, by electromagnetic fields. Quantitative analysis of these first data has only begun, and work with these images and many others not yet processed will continue through the current budget period.

C. Hot-Electron Generation Experiments (UT)

In support of the FSC interest in hot-electron generation from intense laser interactions with solid density plasmas we have, with FSC funding at UT, been investigating hot-electron generation from novel nanoscale targets. In particular, we have investigated hot-electron generation and x-ray production from targets coated with microspheres and pyramidal shaped cone targets which terminate in nanoscale points. The first aspect of this work is motivated by the possibility that spheres with size comparable to the wavelength of the incident laser radiation can result in electric field enhancements through well known Mie resonances. This local field enhancement could then lead to more efficient electron generation and brighter x-ray production.

Hot-Electron Generation from Intense Irradiation of Nanometer Scale Sphere Targets. During the past year, we investigated hard x-ray (>10 keV) generation from fused silica targets coated with a monolayer of monodisperse polystyrene spheres. This idea is schematically illustrated in Fig. 13(a). We investigated this geometry with the hope of observing the effects of field enhancements around spheres of size comparable to the laser wavelength. For example, Fig. 13(b) displays a calculation of the square of the electric field pattern of a 0.25-µm spherical plasma irradiated on a planar plasma surface with 0.4-µm laser light. A clear enhancement of the field near the equatorial plane of the sphere is evident.
We prepared the targets using commercially available polystyrene spheres of diameter 0.26, 0.5, 1.0, 1.5 and 2.9 µm layered on fused silica and subsequently irradiated with laser pulses from the UT THOR laser frequency doubled to 400 nm and focused to intensity \( \sim 2 \times 10^{17} \text{ W/cm}^2 \). An SEM of such a nanosphere target is illustrated in the inset of Fig. 14. X-ray yield at two photon energies as a function of sphere size is illustrated in Fig. 14. A clear peak in the x-ray yield for spheres of 260-nm diameter is observed. These data appear to be strong evidence of the importance of Mie resonant field enhancement in the production of hot electrons at these intensities (which are sub relativistic). The sphere size in which the peak appears surprisingly does not correspond to the sphere size in which we expect a maximum in the electric field from Mie resonances. We believe that the multi-pass stochastic heating of the electrons in the field also plays a role and alters the optimum sphere size. In the coming year under FSC funding we intend to study the specifics of the reason for the peak in hot-electron generation at this wavelength. We will be investigating this through PIC simulations and further experiments.
Hot-Electron Generation from Intense Irradiation of Silicon Pyramid Cone Targets.

The second area of investigation with nanoscale targets has been with silicon conical targets. This work started in ’05 and continued through ’06. These studies are motivated by the FSC interest in hot-electron production and transport in conical targets as well as a desire to develop bright, small source size x-ray sources for backlighting. A major aspect of these studies has been the development of novel, cone shaped targets with very sharp tips (with tip sizes smaller than a wavelength). We have developed guiding structures such as pyramidal and wedge shaped targets made from silicon. This work has been carried through a collaboration between UT and UN Reno. For these experiments sub-micron tips of negative pyramids are etched anisotropically into silicon wafers. After etching, the thickness of the silicon wafer is less than 1µm at the tip of the guiding structure. Titanium foils or other x-ray converter foils can be adhered to the back of the wafer. Under FSC funding, we have studied interactions with both pyramid and wedge shaped indentations. In the case of pyramid target, the laser is interacting with two pairs of opposing walls. In the case of a wedge, the interaction is restricted to one pair of opposing walls. The wedge geometry is designed to investigate polarization effects of micro shaped targets by rotating the orientation of the target with respect to the polarization of the laser. SEM pictures of both square pyramid and wedge targets are shown in Fig. 15. In both cases, the structure terminates with a tip well under 1 µm.

We have conducted experiments irradiating these targets using the THOR laser at 800 nm focused to peak intensity in excess of $10^{19}$ W/cm². X-rays above 2.5 keV were imaged using pinhole camera with beryllium filter. The titanium Kα emissions were measured using both a von-Hamos and a spherical crystal x-ray spectrometer.
Figure 15. SEM images of pyramid (left) and wedge (right) target which are etched in silicon wafers.

Hard x-rays were also measured using a six-channel hard x-ray spectrometer (0.1 ~ 2 MeV). Using the hard x-ray detectors, we have, for example, investigated the very energetic (MeV) photon regime in which x-rays are produced by bremsstrahlung emission. A combination of scintillator/photomultiplier detectors with various cut off filters was utilized for comparing the hard x-ray yield from p and s-polarized wedges and pyramid targets. Figure 16 shows the x-ray yield through three filters for three different target geometries. We observe the highest hard x-ray yield for wedges irradiated with p-polarization and the lowest yield for s-polarized wedges. Kα photon yields and these hard x-ray data indicate a much higher electron temperature for the p-polarized wedges than s-polarized wedges conical targets and flat targets. These results appear to be in accordance with the PIC simulations by Y. Sentoku at Reno, which predict a higher electron temperature for the p-polarized wedges than s-wedges. We are continuing to study the nature of electron transport in these targets with the goal of ascertaining if and how electrons are guided toward the tip.

![Graph showing hard x-ray yield](image)

Figure 16. Hard x-ray yield from p and s-polarized wedges and pyramid targets. P-polarized wedge has highest hard x-ray yield around 1MeV and s-polarized wedge has the lowest. Pyramid is a combination of p and s polarized wedges, resulting in a medium yield.
SIMULATIONS OF ULTRA-INTENSE LASER-PLASMA INTERACTION

A. Channeling in Underdense Plasmas of Fast Ignition Targets (UR)

Of particular concern to the 'hole-boring' scenario in fast ignition is the energy loss through interactions of the ignition pulse with the mm-scale underdense plasma. A channeling pulse, which could be the pre-pulse of the ignition pulse or a separate pulse, has been proposed to produce a low-density channel to reduce the nonlinear interactions of the ignition pulse in the underdense region. In experiments with plasmas formed from laser-pinged solid targets or gas jets, density channels created by \( I = 10^{17-19} \) W/cm\(^2\) pulses were observed [1-3]. Experiments also showed increased transmission for a following pulse in the density channel with \( I = 10^{20} \) W/cm\(^2\) [2]. Two-dimensional (2D) and three-dimensional (3D) particle-in-cell (PIC) simulations of these experiments showed pulse self-focusing in the plasma and channel creation through pulse ponderomotive forces and shock expansion [4]. Most of this previous work was done in 100-µm-scale plasmas.

However, the underdense region of an actual FI target is of a mm-scale. The residue plasma in the channel can continue to interact with the latter part of the channeling pulse and the ignition pulse. Later stages of the nonlinear evolution of the pulse and the channel need to be studied with full-scale simulations. Understanding the channeling process and ignition pulse propagation in the mm-scale underdense region is critical in assessing the viability of the 'hole-boring' scheme and planning for integrated experiments on the next generation FI facilities. In 2006, we have performed 2D PIC simulations with the code OSIRIS showing that channeling in mm-scale plasmas is a highly nonlinear and stochastic process involving pulse self-focusing and filamentation, transverse channel expansion through shock waves, longitudinal plasma piling-up, pulse-hosing and channel bifurcation, and channel self-correction. At \( I = 10^{19} \) W/cm\(^2\) the channel residue plasma density is ~0.05 n\(_c\) and it takes tens to a hundred picoseconds, not a few picoseconds predicted by the linear theory, for the channeling pulse propagation through the mm underdense region.

In our 2D PIC simulations, a channeling pulse of wavelength \( \lambda_0 = 1 \) µm is launched from the left boundary of the simulation box with peak intensities of \( I = 10^{18-19} \) W/cm\(^2\) and a rise time of 495 fs, after which the pulse amplitude is kept constant. The pulse transverse profile is a Gaussian with a full-width-half-maximum intensity spot size of \( w = 16-47 \) µm. The light is focused onto a surface 600-µm away from the left boundary. Both s- and p-polarization are used to infer 3D effects. The initial plasma density profile used is \( n_0 = 0.1 n_c \exp(x/L) \) with \( L = 430 \) µm. The ion-to-electron mass ratio is \( m_i/m_e = 4590\), representing a DT plasma. The electron and ion temperatures are \( T_e = T_i = 1 \) keV. We simulate the region with \( n_0 = 0.1-1.02 n_c \) (\( x = 0-1000 \) µm) in two different setups. In the first one, the whole region is simulated in two separate runs, one for densities \( n_0 = 0.1-0.3 n_c \) and the other for \( n_0 = 0.3-1.02 n_c \). The simulation box size is \( L_x = 477 \) µm (longitudinal) and \( L_y = 262 \) µm (transverse) for the low density portion, and \( L_x = 523 \) µm and \( L_y = 262 \) µm for the high density portion. The grid resolution in these simulations is \( \Delta x = 0.05 \) µm and
\( \Delta y = 0.1 \, \mu m \). Ten particles per cell are used for each species in this setup. In the second setup, a single simulation is used for the entire region with a box size of \( L_x = 987 \, \mu m \) and \( L_y = 401 \, \mu m \). The grid resolution is kept the same but one particle per cell is used for each species. The relativistic self-focusing and filamentation of the pulse occur before significant plasma density perturbations develop (Figure 17(a) and 17(b)). Growing ponderomotive forces from the focused pulse filaments subsequently lead to density filaments, which cause further pulse self-focusing and filamentation. The density filaments grow into mini-channels (Fig. 17(c)). A longitudinal modulation in the ponderomotive force, probably seeded by the relativistic modulational instability, destroys the mini-channel walls (the density maxima) and sets off the merging of neighboring mini-channels, eventually forming a single density channel centered around the original pulse intensity maximum (Fig. 17(d)). At the end of this stage, the electron temperature reaches \( \sim 500 \, \text{keV} \) at the channel walls and an electrostatic shock is launched there to move the walls at a fairly constant speed of 0.03c. The channel eventually expands to be wider than the initial pulse width. The transverse expansion process repeats as the pulse propagates to gradually extend the channel toward the critical surface. In the meantime, a density jump is formed at the head of the channel through a 'snowplow' effect. The density jump

![Figure 17](image-url)
grows as the channel digs into higher density and can reach a value higher than the initial local density (Fig. 18(a)). In regions with $n_0 > 0.3n_c$, the density jump exceeds $n_c$ (Fig. 18(b)), thus making the pulse propagation similar to the 'hole-boring' process. The density jump slows down the pulse speed below the group velocity in the initial local density.

![Figure 18](image18.png)

Figure 18. The transversely averaged plasma density in the channel. (a) The low density (0.1 - 0.3 $n_c$) case; (b) the high density (0.3 - 1 $n_c$) case.

While its transverse expansion is regular, the channel's longitudinal advance is stochastic and dynamic. The channel can bend toward one side of its center due to a hosing instability of the laser pulse in the channel. The pulse is not always contained in the bent channel and can break out of the sidewall to form a new branch of the channel. Both branches can advance deeper into the plasma, leaving a narrow plasma 'island' in the middle of the entire channel (Fig. 19(a)).

![Figure 19](image19.png)

Figure 19. Plots of the ion density. The channel bifurcation seen at $t=3.4$ ps is later self-corrected at $t=7.1$ ps, leading to a single channel in which an ignition pulse can freely propagate.
Eventually, the 'island' is pushed away by the pulse and the two branches merge to form again a single channel (Fig. 19(b)). This process of bifurcation-merge can repeat in a simulation lasting ~10 ps and provide a mechanism to self-correct deviations in the channel propagation caused by the hosing-bending instability. Over time, the channel direction remains along the pulse propagation direction. To measure the channel advance speed in this dynamic environment, we define the channel as any location where the average plasma density is less than $n_r=0.05n_c$, which is approximately the residue density in the channel in all simulations, independent of the initial densities. More specifically, the density is averaged transversely around the pulse center $y_c$, $y_c-w/2<y<y_c+w/2$, with $w$ the initial pulse width. The channel front $X_c$ is defined as the location when the average density is $n_r$ and the channel advance speed is $v=\frac{dX_c}{dt}$. Figure 20 shows that $v$ is stochastic but generally $v/c>0.1$ for $I=10^{19}$ W/cm$^2$. For $I=10^{18}$ W/cm$^2$, preliminary analysis shows that the residue density does not change significantly but the advance speed is much lower, $v/c\sim0.02$.

![Image](image.png)

Figure 20. Channel advance speed at different initial plasma densities.

References

B. Integrated PIC Simulations of Hot-Electron Generation and Transport to a Dense Core (UCLA)

A variety of improvements have been made in 2006, extending the modeling capabilities of OSIRIS. These include improved particle collisions and improved absorbing boundary conditions for the fields. The latter allow for the implementation of absorbing boundary conditions in more than one direction, thus preventing particles that leave the simulation box from coming back into the simulation. A particle collision package has been added for use with Fast Ignition simulation parameters. This allows energy and momentum conserving high-density core regions to be added to the simulations.

Fast ignition is critically dependent on the amount of energy that can be transmitted from the critical surface to the dense (~300g/cm$^3$) core. Our simulations seek to find out how much energy is transmitted into the dense core and how we can increase the amount of energy deposited into the dense core in non-cone targets. The energy spectrum of the electrons reaching the dense core is as important as total energy carried by these electrons. If the energy of the individual electrons is too high, they will pass through the core without collisionally heating it. In our model, no cone is used to attempt to focus the electrons. We use large scale PIC simulation to model the Fast ignition target. We use isolated targets as we have found the boundary conditions can significantly affect the simulation results. In the most recent simulations, we model a 50-µm radius target at 100 times the critical density. An absorbing region 50-µm from the critical surface is used to model the dense collisional core where electrons deposit their energy, as shown in Fig. 21.

Figure 21. Illustration of the target used in simulation. The red area is 100 times the critical density. The collisional core is modeled using a drag on the lower-energy particles.
The target is irradiated by a laser pulse with intensity of $5 \times 10^{19} \text{ W/cm}^2$ and duration of 2.5 ps. Figure 22 shows the net power entering the core of the target as a function of time. High energy particles are not stopped in the core so the net power entering the core is dominated by lower energy particles. As seen in Fig. 23, the energy flux is peaked around the core region showing that most of the energy at that plane is flowing into the core.

Figure 22. Net power entering the dense core. Although the efficiency is low early in the simulation, it continues to grow in time from 2% to 6%.

Figure 23. Electron energy flux forward through the plane 2 µm in front of the core. This shows that the energy flux is concentrated in the area of the dense core.

In this simulation, the energy does not flow evenly across the collisionless plasma instead it forms a hot spot in front of the laser interaction region as shown in Fig. 24. This hot spot moves forward with time causing the energy flux into the core to grow with time (Fig. 22).
Figure 24. On the left, it is shown the electron energy distribution in a fast ignition target after 2.5 ps. A hot spot is formed in front of the laser/critical surface interface. This hot spot moves towards the core. On the right, the spatial distribution of the energy flux forward carried by the electrons shows that the hot spot on the left is moving forward increasing the amount of energy delivered to the core.

The energy spectrum of the electrons reaching the core is as important as the amount of energy that reaches the core. Lower energy electrons (~1 MeV) deposit their energy in the core much more efficiently than higher energy electrons. Figure 25 shows that the energy spectrum of the electrons reaching the core is significantly lower (mostly <1 MeV) than the spectrum of the electrons generated at the critical surface. This is an important result since it shows that higher-intensity lasers can be used to generate the ignitor pulse.

Figure 25: Energy spectrum of the electrons in the central region (<40 μm). Note that the spectrum of the electrons reaching the core (at 500 c/ωp) shows lower energies than the spectrum of the electrons generated at the critical surface (~150 c/ωp).
C. Integrated PIC Simulations of Cone-Guided Fast Ignition Targets

Recent experiments at ILE using the GEKKO laser coupled to a PW laser system have successfully tested the cone-guided concept [1]. Compressed cores with densities of 50-100 g/cm$^3$ and diameters of 30-50 $\mu$m, were produced at about 20-30 $\mu$m from the cone tip. It was shown that the PW laser pulse enhances the neutron yield by two orders of magnitude. Such a large increase in yield is consistent with a core temperature of 1keV. Up to date, there is still no consensus on the core heating mechanism. Hybrid simulations have been widely used [2,3] to study the electron transport in cone-guided fast ignition. In hybrid code simulations, the hot-electron generation is not self-consistently calculated. Instead, the hot-electron temperature is assumed to follow the ponderomotive scaling [3]

$$T_h = m_e c^2 \left( \sqrt{1 + a^2} - 1 \right),$$

(1)

where $m_e$ is the electron mass, $c$ is the speed of light, and $a$ is the normalized laser field $a = eE/m_e c \omega$ and $\omega$ is the laser frequency. For example, $a=10$ corresponds to a laser intensity of $1.4 \times 10^{20}$ W/cm$^2$ and a hot-electron temperature of $T_h \sim 4.6$ MeV from Eq. (1). Such energetic electrons would pass through the dense core without collisionally heating it. The large hot-electron energy predicted by the ponderomotive scaling [Eq. (1)] is an issue of crucial importance for fast ignition and needs to be studied in detail.

In 2006, we have carried out PIC simulations of cone-guided fast ignition through a collisional PIC code. Such simulations include all the relevant physics for a self-consistent analysis of cone-guided fast ignition. Results of these simulations have indicated that electromagnetic instabilities (such as the Weibel instability) develop around the cone target where the plasma density is less than a few hundred times the critical density. The simulations also show that no significant fields are present in or near the core area. This indicates that the core heating is mainly due to collisional processes. The dominant core heating mechanism was identified as the friction heating between hot and bulk electrons in the simulation. We also found that the hot-electron temperature observed in the simulations is lower than predicted by the ponderomotive scaling in Eq. (1). This was particularly evident after the preplasma inside the cone was blown away by the strong photon pressure. A new hot-electron temperature scaling has been derived, and confirmed by the simulations. The simulations are carried out using the high performance, two-dimensional collisional Particle-in-Cell (PIC) code PICLS2d. The binary collision module in the code is based on Takizuka and Abe's model [4], extended to treat relativistic collisions [5] and collisions between weighted macro-particles [6]. The Coulomb logarithm is calculated based on the ratio of the projectile electron wave length to the Debye length [5].
In order to simulate extremely dense, low temperature (<1 keV) plasmas, a fourth order interpolation scheme is used for the fields and current calculations. Furthermore, the reduced PIC technique is applied for computations in large density scale plasmas, with densities ranging from sub-critical to 100,000 times the critical density. The basic idea behind the reduced PIC method is the collisional damping of the kinetic effects in dense plasmas [7]. The details of this method, including the relativistic collision model, are being prepared for publication. The initial plasma density profile on the laser axis is shown in Fig. 26 (a). The plasma is modeled as a fully ionized hydrogen plasma with 150 eV initial temperature. The core density is $2 \times 10^{25}$ cm$^{-3}$, corresponding to 100 g/cm$^3$ for a DT plasma, and its diameter is 10 µm. The core is surrounded by the coronal plasma with an exponential density profile varying from $10^{20}$ to $2 \times 10^{25}$ cm$^{-3}$. The cone target, with density $5 \times 10^{23}$ cm$^{-3}$, is placed at 25 µm from the center of core. The cone has a 30 degree opening angle as shown in Fig. 27 (b). The tip size and thickness are 10 µm and 5 µm, respectively. As shown in Fig. 26 (a), a preformed plasma is placed inside the cone. The normalized laser amplitude is $a=10$ corresponding to the intensity of $1.4 \times 10^{20}$ W/cm$^2$. The laser pulse has a semi-infinite duration starting with 150 fs rise time with a Gaussian profile. The total simulation time is about 1 ps. The input energy in the laser spot (gaussian profile of 10 µm diameter) is ~130 J in 1ps, and about 85% of the energy is absorbed through the laser-cone interaction. Our choice of the plasma parameters is based on the results of hydro simulations [8], and the plasma density behind the cone target is taken equal to the solid density. The latter is large enough to suppress the sheath fields excitation behind the cone tip thus preventing the ion acceleration at the rear surface of the cone tip. Although the size of the simulated target is significantly smaller than an ignition scale FI target, most of the FI physics issues are similar. Note that since the cone target is modeled by hydrogenic plasmas, the hot-electron scattering inside the cone target is underestimated in this simulation. The electron scattering in the cone target will be the subject of future work. In our simulation, the system size is 50 µm x 42 µm. We used a 3750 x 3168 mesh and 3.6$\times 10^8$ particles (15 particles per cell for each species and weighted particles are used to reproduce the density profile). Absorbing boundary conditions were used for the fields and particles. The particles arriving at the boundaries are reflected with the initial thermal velocity. Figure 26 (a) shows the longitudinal
electron phase plot at 270 fs on the laser axis ($Y=21 \, \mu m$). Apparently there are two hot-electron groups: one is extremely energetic with 50 MeV maximum energy, and the other has lower energies in the few MeV range. The laser is reflected and focused toward the tip of cone leading to a two-fold amplification of the intensity. The peak electron temperature in the cone target is about 6 MeV, which is close to the predictions of the ponderomotive scaling [Eq. (1)] with the focused intensity.

Figure 27: (a) Electron energy spectrum observed in the core region marked with a broken circle in (a'). Figure (a') shows the electron energy density [keV$\cdot n$] at 200 fs. The energy density is normalized by $3.6\times10^{23}$ cm$^{-3}$. (b) Electron density [cm$^{-3}$] at 330 fs, and (c) at 860 fs. (d) Quasistatic magnetic fields [MG] at 860 fs. A white, broken line represents the iso-density curve at $10^{23}$ [cm$^{-3}$].
The very energetic electrons have a large angular divergence of about 30 degrees from the laser axis, as shown in the electron energy density plot in Fig. 27 (a'). On the other hand, the divergence of the lower energy group is ~10°, in agreement with the angle calculated by taking the ratio of the transverse (the normalized amplitude \( a \)) and longitudinal momenta (\( a^2/2 \)) in the JxB acceleration. With such a small opening angle, the less energetic electrons collide with the dense core and efficiently heat it.

The two groups of hot electrons are clearly seen in the energy spectrum shown in Fig. 27 where the core region is marked by a broken circle (see Fig. 27(a')). At early times (130 fs), only very energetic electrons are produced, since the laser interacts with the preformed plasma inside the cone. About 100 fs later, which is the time scale of the ion motion, the hot-electron energy drops. This drop is due to the interface steepening occurring after the preplasma is swept away as shown in the density profile of Fig. 27 (b). A steep density profile causes the laser light to directly interact with the dense cone material. As the cone target temperature rises, the pressure of the plasma in the cone overcomes the light pressure and the plasma expands back. This causes the laser absorption to increase, and the hot-electron energy to rise again [9]. Figure 26(b) shows the longitudinal momentum versus the local plasma density at the particles’ initial position near the laser axis. Note that the hot electrons generated at densities below a few hundred times the critical density are extremely energetic, due to wave particle mixing effects. There are virtually no high energy electrons generated above that density. Figure 27(d) shows the quasi-static magnetic fields at 860 fs. Note that the magnetic fields do not develop at early times, since the Weibel instability is damped by collisions. However, at later times, the local plasma temperature rises and the collisional damping becomes weaker, thus allowing the magnetic field to grow from the instability. Nevertheless, the quasi-static magnetic filaments are localized at densities below a few hundred times the critical density and never reach the core area. Such a density range corresponds to the region of strong electron heating shown in Fig. 26(b). This implies that the kinetic instability is suppressed in the high dense region, and the heating is due to collisional processes. Similar features were observed in the longitudinal modes from the 1-D simulations in Ref. [7]. The mean energy in the core region after about 1 ps is 1.5 keV for the ions and 45 keV for the electrons (including the hot electrons). The coupling efficiency in the region with a density above \( 10^{24} \text{ cm}^{-3} \) (marked by the outer circle in Fig. 28(a)) is 33.3% for the electrons and 6.4% for the ions. In the core area marked by the inner circle in Fig. 28(a), the coupling efficiency is 13.1% for the electrons and 2.4% for the ions. In Fig. 28, the history of the maximum energy gain in the core is plotted. Note that the rapid heating occurs during the early times (250 – 400 fs) and a slower heating rate develops after 400 fs. The core heating during the early stage is mainly due to the resistive heating, which saturates after the core temperature exceeds about 500 eV (gain ~3) [7]. At later times the collisional energy transfer between the fast and bulk electrons becomes dominant. Fast ions are also produced and form a bow shape ion wave. The ion energy of about 3 MeV is consistent with the sweeping acceleration mechanism described in Ref. [10]. The fast ion energy is only 0.1% of the input laser energy.

The effect of the target density on the hot-electron energy is studied by varying the cone target density in the simulations. It was shown in Ref. [11] that the hot-electron energy decreases as the target density increases. Such a density dependence can be explained using the following conjecture. Since the intense laser light stops at the
relativistic critical density, $\gamma_{os} n_c$, (here $n_c$ is the critical density of the laser light and $\gamma_{os}$ is the electron's relativistic factor in the laser light), when the plasma scale length exceeds the plasma skin depth, electrons are accelerated through the laser interaction occurring at the critical surface within a distance about equal to the plasma skin depth, $c/\omega_p(n_c) = c/\omega$, which is independent of the laser intensity. When the plasma scale length is shorter than $c/\omega$, and the density increases sharply from the critical density to the target density $n_t$ (here $n_t > \gamma_{os} n_c$), the electrons are not fully accelerated since the acceleration distance is limited to the $c/\omega_p(n_t)$. Since the particle energy is proportional to the acceleration distance, one can rewrite the ponderomotive scaling in the following form,

$$T_h = m_e c^2 (\gamma_{os} - 1) \sqrt{\gamma_{os} n_c / n_t}$$

(2)

We have performed a set of simulations by changing the cone target density and computed the hot-electron temperature of the low energy group at 300 fs. The preplasma condition was the same in each simulation. Results are summarized in Fig. 29 and compared with the new temperature scaling in Eq.(2). The results show a clear $1/\sqrt{n}$ dependence in agreement with Eq. (2). Note that the hot-electron spectra at 100 fs (before the preplasma is swept away) are identical. In summary, we have carried out a detailed study of cone-guided fast ignition using the collisional PIC code PICLS. We have shown that electromagnetic instabilities develop around the cone target and remain confined in the region where the plasma density is less than a few hundred times the critical density. This indicates that the core heating is mainly done by collisional processes and not by anomalous heating [12] caused by electromagnetic instabilities. The dominant core heating mechanism was identified as the drag heating between the hot and bulk electrons.

![Figure 28: Time history of energy gain in the core region. The gain is calculated by dividing the local energy by the initial temperature 150 eV. (a) Electron energy density and (b) ion energy density at 860 fs.](image)
We also found that the hot-electron temperature observed in the simulation is inversely proportional to the square root of the cone target density, after the preplasma inside the cone was blown away by the intense photon pressure. This hot-electron temperature scaling is confirmed by the results of the simulations. We derived a new hot-electron temperature scaling law indicating that the hot-electron energy might be tailored by varying the cone density. The new temperature scaling can also be used to determine the hot-electron conditions used as input in hybrid simulations.

![Figure 29: Plot of the hot-electron temperature behind the cone target (after the preplasma is blown away, at 330 fs) versus the core density. The solid line is the corrected scaling, Eq. (2). Open circles indicate that the conversion efficiency from input laser energy to hot electrons is weakly dependent on density.](image)

References


D. Comparison of MIT’s Stopping Power Model CELSA to Cold-Matter Monte-Carlo Calculations (MIT)

In addition to the experimental efforts, MIT has conducted theoretical work comparing our CELSA (Coupled Energy Loss and Scattering Approximation) calculations to cold-matter Monte-Carlo calculations. Hot-electron transport has been examined in the single-particle regime in cold matter and in a fully ionized, classical cold plasma of solid-density using the Monte Carlo code ITS 3.0 and the CELSA plasma
Primary electron penetration in DT ice has been found to be ~40% larger than in a DT plasma of equivalent density. This is attributed primarily to the plasma wave contribution to the plasma stopping power. Scattering is quantified by range straggling and lateral blooming; its ratio to penetration was found comparable in DT plasma and ice. Similar trends are found for higher Z materials, though direct quantitative comparison requires a to-be-performed normalization of the outputs of the two models. The results of this work have recently been submitted to the Journal of Applied Physics for publication. Figures 1 and 2 illustrate aspects of this work.

Figure 30. Stopping powers of higher Z plasmas generally differ more strongly from their cold matter values. However, in common with hydrogenic stopping, plasma stopping is ~40% larger than cold-matter counterparts, an effect primarily attributable to the plasma wave contribution. These calculations bear directly on issues of both preheat and energy deposition in FI capsules.

Figure 31. Pictorial representations of the primary electron endpoint of a 1 MeV beam into cold-matter DT, Be, Al, Cu, and Au. As expected, the qualitative effects of scattering become more pronounced for higher Z materials, leading to a “rounder” shape in the electron endpoint, a result shared with plasma calculations. Penetration decreases with increasing Z, even when considered in units of areal density. Here the dashed lines represent the range of the straight-line continuous slowing down approximation (CSDA range) (tabulated by Berger and Seltzer). These calculations are directly relevant to preheat, adiabat shaping, capsule compression, energy deposition and ignition for fast ignition capsules.
A. Target Designs and Gain Curves for Fast Ignition

Similar considerations to those used in the design of direct-drive implosions can be employed to design targets and laser pulses to optimize the fuel assembly for fast ignition. Hydrodynamic simulations and experiments are then used to characterize the compressed core. Thermonuclear gains can be obtained from numerical simulations of the interaction of an energetic electron (or proton) beam and the compressed core. The first step is the design of optimized implosions [1] for fast ignition. The implosions can be slow since central high temperatures are not important and the temperature is proportional to the implosion velocity. For a given driver energy, slow implosions require massive shells, leading to large fuel masses and therefore large gains. Low velocities lead to low densities since the density is directly proportional to the implosion velocity. However, since the density is also inversely proportional to the inner shell adiabat, one can design a fast-ignition implosion of a massive shell driven at a low implosion velocity as long as the inner adiabat $\alpha$ is kept low enough to compensate for the low implosion velocity and still produce the high densities required for ignition. Optimized fast-ignition targets [1,2] are massive shells of DT fuel (preferably wetted foams to improve the laser absorption) driven on a very low inner-surface adiabat. Another advantage of keeping the adiabat low is that the areal density increases for lower adiabats, leading to a higher burn fraction and a higher gain. Laser pulses for very low adiabat ($\alpha < 1$) implosions are typically difficult to design and to implement since the laser intensity needs to be kept initially very low to drive a relatively weak shock that does not fully ionize the target. The adiabat, defined here as the electron pressure of the partially ionized DT divided by the Fermi pressure at full ionization, can have a value less than unity. After the first shock has been launched, the laser intensity needs to be slowly increased until it reaches a flat-top value that can be as high as hundreds of times the initial value. A contrast ratio (intensity ratio between the flat-top and the foot portions of the laser pulse) greater than 100 to 150 is probably hard to achieve with current laser technology. However, using the same class of pulses used to shape the adiabat with the relaxation technique [3], the main pulse can be designed with a contrast ratio typically half of what would have been required without the initial intensity spike. The use of adiabat shaping here is motivated more by considerations of laser technology than by hydrodynamic stability. As indicated in Ref. [1], the optimized fuel assembly for fast ignition can be obtained by driving massive shells of wetted foams at a velocity of about $1.7 \times 10^7$ cm/s with an inner surface adiabat of $\alpha_{\text{inner}} \approx 0.7$. Such implosions lead to high areal densities and high densities in the range of 300 to 500 g/cm$^3$. Once the optimized ignition target and laser pulse shape have been defined, the gain calculation can be carried out. The maximum gain $G_M = E_F / E_c$ is defined as the ratio between the thermonuclear energy $E_F$ and the compression-laser energy on target $E_c$. Then the total gain $G_T = E_F / E_T$ is defined as the ratio between the thermonuclear energy and the total laser energy on target including the petawatt laser energy, $E_T = E_c + E_{\text{pw}}$. The conversion efficiency of the petawatt laser energy into collimated fast particles is defined as $\eta_{\text{pw}} = E_{fp} / E_{\text{pw}}$, and the fast-particle energy $E_{fp}$ is set.
equal to the minimum energy required for ignition $E_{\text{ig}}^\text{min}$. All the complications related to the hot-electron generation and transport are incorporated in $\eta_{\text{pw}}$. The scope of this section is limited to the target gain calculation parametrized with $\eta_{\text{pw}}$, and the issues related to the hot-electron generation and transport are not addressed. Using a value of $1.7 \times 10^7$ cm/s for the implosion velocity $V_i$, a laser wavelength of 0.35 $\mu$m, a laser intensity of $10^{15}$ W/cm$^2$, and $\alpha_{\text{inner}} = 0.7$ leads to a maximum gain formula dependent on the laser energy $E_c$:

$$G_M \approx \frac{743(1-E_{\text{cut}}/E_c)^\mu}{1 + 21/\left[\xi E_c^{0.33}\right]}$$  \hspace{1cm} (2.3.3)$$

where $E_c$ is in kJ and $\xi$ represents the fraction of the maximum total areal density available for the burn. The ad-hoc term $(1-E_{\text{cut}}/E_c)^\mu$, where $E_{\text{cut}}$ is a cutoff energy, has been introduced to account for the yield deterioration of small targets for which the electron-beam size is of the order of the compressed core size, occurring for $E_c \sim E_{\text{cut}} \approx 40$ kJ. The factors $\mu$ and $\xi$ are of order unity and are determined by a numerical fit to 2-D burn simulations. It is important to emphasize that slow implosions with $V_i < 2 \times 10^7$ cm/s are not significantly affected by the Rayleigh–Taylor instability. The in-flight aspect ratio is very low for such low implosion velocities, and the hydrodynamic instabilities have a negligible effect on the implosion performance [4]. Figure 32 shows the result of a two-dimensional (2-D) multimode simulation of a 200-kJ fast-ignition target implosion.

Figure 32. Density contour plots of a two-dimensional DRACO simulation of a wetted-foam fast-ignition target including modes $\ell = 4$ to 200, (a) at time $t = 0$ and (b) at the end of the acceleration phase. The simulation includes NIF-like laser imprinting and laser smoothing using 1-THz SSD.
The laser nonuniformities typical of a NIF-like laser with 1-THz, 2-D smoothing by spectral dispersion (SSD) are included. Figure 32(a) shows the initial wetted-foam target and Fig. 32(b) the imploding shell at the time of laser shutoff (end of the acceleration phase). The outer surface of the shell is only slightly perturbed by the Rayleigh–Taylor instability, indicating that the implosion is approximately one dimensional. This is an important consideration as it allows use to be made of the 1-D code LILAC to simulate the generation of the dense core of the fast-ignition fuel assembly (in the absence of a cone). The burn phase of the fast-ignited capsule is modeled by starting from the 1-D fuel assembly and using the 2-D hydrodynamics code DRACO to simulate the ignition by a collimated electron beam and the subsequent burn. DRACO includes electron-beam energy deposition into the dense fuel according to relativistic slowing-down theory. The hot-electron energy (1 to 3 MeV), beam radius (15 to 25 µm), and pulse length (5 to 10 ps) are varied to find the minimum ignition energy of about 15 kJ. As long as fast ignition is triggered, the thermonuclear energy yield is approximately independent of the electron-beam characteristics. Burn simulations have been performed of several fuel assemblies characterized by the implosion parameters stated above [2]. The targets used in the simulations (Fig. 33 shows three of them) are massive wetted-foam targets with initial aspect ratio (outer radius divided by thickness) of about 2, driven by 351-nm laser energies from 50 kJ to 2 MJ scaled such that the maximum intensity $\sim 1 \times 10^{15}$ W/cm$^2$.

Figure 33. Wetted-foam fast-ignition targets designed for 750-kJ, 200-kJ, and 100-kJ direct-drive implosions using a 351-nm laser driver.
The relaxation laser pulses [3] for the 200-kJ and 750-kJ targets are shown in Fig. 34 with the main pulse length varying from 15 ns for the 200-kJ target to 22 ns for the 750-kJ target. In all cases, the hot electrons are injected after the time of peak areal density, when the average density of the compressed core is about 300 to 400 g/cm$^3$ and the $\rho R$ of the compressed shell is close to its maximum value.

Figure 34. Adiabat-shaping 351-nm laser pulses used for the 200-kJ and 750-kJ targets.

The neutron yields for the 100-kJ, 200-kJ, and 750-kJ assemblies are $2.0 \times 10^{18}$, $6.4 \times 10^{18}$, and $4.2 \times 10^{19}$, respectively, and the thermonuclear energy yields are 5.6, 18, and 118 MJ, respectively. The results of these simulations are used to determine $\xi \approx 0.7$ and $\mu \approx 1.1$, leading to a maximum gain

$$G_M = \frac{743 \left(1 - \frac{E_{\text{cut}}}{E_c}\right)^{1.1}}{1 + \frac{30}{\xi E_c^{0.33}}},$$  \hspace{1cm} (1)$$

where $E_c$ is in kJ and $E_{\text{cut}} = 40$ kJ. The gain curve representing the maximum gain is shown in Fig. 35(a) with the results of the burn simulations superimposed. Even a modest-size UV laser driver with an energy of 200 kJ can produce a fuel assembly yielding a maximum gain close to 90. Using $E_{\text{ig}}^{\text{min}} = 15$ kJ [5] and setting the petawatt laser energy equal to $E_{\text{pw}} = E_{\text{ig}}^{\text{min}}/\eta_{\text{pw}}$, the total target gain is plotted for different values of the conversion efficiency $\eta_{\text{pw}}$ in Fig. 35(b) for the three values of $E_{\text{pw}}$. Even in
the case of only 10% efficiency, the target gain from a 200-kJ fuel assembly is still remarkably high ($G_T = 70$), indicating that fast ignition can achieve significant gains with relatively small compression drivers. However, achieving the requirement of a 15-kJ collimated beam still remains a very challenging task.

![Graph](image)

**Figure 35.** (a) Maximum gain (fusion energy/compression driver energy) versus compression driver energy. The points are the results of burn simulations while the curve is from Eq. (1). (b) Total target gain (fusion energy/total laser energy on target) versus compression driver energy for $E_{pw} = 50$ kJ ($\eta_{pw} = 0.3$), $E_{pw} = 75$ kJ ($\eta_{pw} = 0.2$), and $E_{pw} = 150$ kJ ($\eta_{pw} = 0.1$); in each case, 15 kJ is assumed to be coupled into collimated fast particles.
B. High $\rho R$ Implosions for Fast Ignition Fuel Assembly

In the previous section and in Refs. [2,4], it was shown that it is possible to achieve high gains in fast ignition if the fuel can be assembled on a low adiabat and with a low implosion velocity, leading to large fuel masses compressed to densities of hundreds of g/cm$^3$. Recently, a series of experiments [6] have been carried out on OMEGA to optimize the fuel assembly for fast ignition through low-velocity, low-adiabat implosions using 40-$\mu$m-thick CH shells with 430-$\mu$m outer radius. The targets, shown in Fig. 36(a), were filled with D$_2$ or D$^3$He and driven by the 20-kJ laser pulse shown in 36(b), which provides adiabat shaping using the relaxation technique [3]. One-dimensional simulations of the implosion indicate that the implosion velocity was about $2 \times 10^7$ cm/s and the inner adiabat was $\alpha_{\text{inner}} \approx 1.3$.

Figure 36. (a) 40-$\mu$m-thick CH target and (b) the 20-kJ OMEGA laser pulse used to drive the shell on an adiabat $\alpha_{\text{inner}} = 1.3$ with an implosion velocity of $2 \times 10^7$ cm/s.

The primary experimental diagnostics were wedge-range-filter proton spectrometers [7,8] that measured the spectra of the protons from the primary D + $^3$He fusion reactions for D$^3$He fills and those from the secondary D + $^3$He reactions for D$_2$ fills. Typical proton spectra are shown in Fig. 37(a) for 25-atm D$_2$ and D$^3$He fills. Each point of the spectrum corresponds to a different downshift and therefore to a different $\rho R$. The predicted time dependence of $\rho R$ is given in Fig. 37(b) for a D$_2$-filled target, together with predicted and measured neutron production rates. The $\rho R$ increases during the burn and the burn is quenched near the time of peak areal density. Thus, the energy downshift of the low-energy tail of the spectrum in Fig. 37(a) represents a measure of the peak $\rho R$ during the burn that is approximately equal to the simulated peak $\rho R$.

This is verified by reconstructing the proton spectrum using the simulated $\rho R$ evolution and the experimental neutron rate of Fig. 37(b). This is justified because the temporal
dependence of the neutron rate is predicted to be close to that of the secondary proton rate and the rises of the simulated and measured neutron rates are closely matched (Fig. 37(b)).

At each time, the proton energy is downshifted according to the simulated $\rho R$ and the energy loss formula of Ref. [9]. The resulting proton spectrum for a D$_2$-filled target agrees well with the experimental spectrum shown in Fig. 38, indicating that the simulated evolution of $\rho R$ is fully consistent with the measured spectrum during the burn.

Figure 38. Experimental proton spectrum (solid) compared to the predicted spectrum using 1-D simulations and experimental neutron rates for shot 43075. The dashed curve is for the extended 1-D source, the dashed-dotted curve is for a point source and the solid curve is the average of the two.
This provides the needed confidence to infer the maximum $\rho R$ from the maximum downshift of the spectrum, leading to a peak $\rho R$ of 0.26 g/cm$^2$. Table I shows the burn-averaged areal density $\langle \rho R \rangle$ and the maximum areal density during the burn $\rho R_{\text{max}}$ derived from the proton spectrum for several shots. The measured neutron yields of the D$_2$ targets were in the range of $2 \times 10^{19}$ to $4 \times 10^9$, large enough to generate a measurable neutron time history, well above the noise level as shown in Fig. 37(b), allowing $\langle \rho R \rangle$ and $\rho R_{\text{max}}$ to be simulated as described above. These simulated values, also given in Table I, agree well with the experimental values. It was not possible to simulate the $\rho R$ evolution during the neutron production for D$_3$He-filled targets since no useful neutron rates were measured due to the low yields of the D$_3$He reactions. For these targets, the measured $\rho R_{\text{max}}$ reported in Table I was based on the maximum downshift in the spectrum (7 MeV for the spectrum shown in Fig. 37(a), corresponding to an areal density at burn truncation of 0.24 g/cm$^2$) and the simulated $\rho R_{\text{max}}$ was the maximum value of $\rho R$ obtained in the simulation. Similar results are seen in Table I for both target types and minor variations in the fill pressure and laser energy.

Table I: Measured and simulated areal densities in g/cm$^2$ for different fills and gas pressures (in atm). (The laser energy in shot 43114 was only 16 kJ, compared with the nominal 20 kJ.)

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Gas fill</th>
<th>Pressure</th>
<th>Measured $\langle \rho R \rangle$</th>
<th>Simulated shell $\langle \rho R \rangle$</th>
<th>Measured $\rho R_{\text{max}}$</th>
<th>Simulated $\rho R_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>43074</td>
<td>D$_2$</td>
<td>34</td>
<td>0.133</td>
<td>0.138</td>
<td>0.249</td>
<td>0.238</td>
</tr>
<tr>
<td>43075</td>
<td>D$_2$</td>
<td>25</td>
<td>0.146</td>
<td>0.144</td>
<td>0.261</td>
<td>0.261</td>
</tr>
<tr>
<td>43107</td>
<td>D$_2$</td>
<td>25</td>
<td>0.122</td>
<td>0.132</td>
<td>0.240</td>
<td>0.275</td>
</tr>
<tr>
<td>43114</td>
<td>D$_2$</td>
<td>25</td>
<td>0.128</td>
<td>0.112</td>
<td>0.227</td>
<td>0.227</td>
</tr>
<tr>
<td>43109 + 43112</td>
<td>D$_3$He</td>
<td>33</td>
<td>0.128</td>
<td>—</td>
<td>0.24</td>
<td>0.250</td>
</tr>
<tr>
<td>43110 + 43113</td>
<td>D$_3$He</td>
<td>25</td>
<td>0.130</td>
<td>—</td>
<td>0.24</td>
<td>0.281</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.131</td>
<td>0.132</td>
<td>0.243</td>
<td>0.255</td>
</tr>
</tbody>
</table>

The mean value of the measured burn-averaged $\rho R$ over all shots is 0.131±0.017 g/cm$^2$ and agrees well with the mean simulated value of 0.132 g/cm$^2$. The peak $\rho R$ measured from the tail of the spectrum and averaged over all shots is 0.24±0.02 g/cm$^2$ and compares favorably with the simulated value of 0.255 g/cm$^2$. Such $\rho R$’s are the largest areal densities assembled on OMEGA to date. The peak $\rho R$ across the entire core (i.e., 2 $\rho R_{\text{max}}$) is ~0.5 g/cm$^2$, sufficient to slow down 2-MeV electrons. For fast-ignition-equivalent empty CH capsules, 1-D simulations indicate a maximum $\rho R$ of 0.66 g/cm$^2$. 49
or an areal density of ~1.3 g/cm² through the entire core, enough to stop 4.5-MeV electrons. Such dense cores are optimal for studying hot-electron coupling efficiencies in integrated fast-ignition experiments. These results show that low-velocity, low-adiabat implosions are a viable approach to assembling high-areal-density fuel for fast ignition.

References