National Nuclear Security Administration

DOE/NA-0044

2016 Inertial Confinement Fusion Program Framework

- *Ten-Year High Energy-Density Science Strategic Plan*
- *Integrated Experimental Campaigns*
- *Priority Research Directions*
- *National Diagnostics Plan*

U.S. DEPARTMENT OF ENERGY

ICF
Inertial Confinement Fusion & High Yield

✧ On the Cover

The Inertial Confinement Fusion (ICF) Program's mission is to provide the most extreme temperature and pressure conditions spanning states of condensed matter to very hot and dense plasmas for the National Nuclear Security Administration's Stockpile Stewardship Program.

This mission requires some of the most advanced experimental and computational capabilities in the world. Most important to the success of this mission are the highly trained scientists, engineers, and technicians that dedicate their lives to this mission, and are a key part of the intellectual capital that underpins the nuclear weapons stockpile.

Pictured on the cover are major components, experiments, computations, and people from a variety of facilities and facets of the ICF Program that are described in more detail in this document.

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U.S. DEPARTMENT OF ENERGY

ICF
Inertial Confinement Fusion & High Yield

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

National Nuclear Security Administration

May 11, 2016

MEMORANDUM FOR NNSA'S HIGH ENERGY DENSITY PHYSICS AND INERTIAL CONFINEMENT FUSION COMMUNITY

FROM: KEITH R. LECHIEN
DIRECTOR
OFFICE OF INERTIAL CONFINEMENT FUSION

SUBJECT: 2016 Inertial Confinement Fusion Program Framework

It is a pleasure to present the first-ever comprehensive national Inertial Confinement Fusion (ICF) Program Framework. This Framework was developed over 20 months using input from hundreds of technical staff, program managers, and academic partners from over a dozen institutions with direct interest in the ICF and related high energy density (HED) aspects of National Nuclear Security Administration's (NNSA) Stockpile Stewardship Program (SSP).

In the January 2015 Directors' letter on the importance of the SSP's ICF and HED efforts, the three NNSA Laboratory Directors pledged their delegates to "[meet] regularly in 2015 to ensure progress towards [an] integrated and coordinated National HED effort." This Framework is the product of those efforts, and this document summarizes the Framework with reference to a more comprehensive description connected to the program requirements and plans. The document will be revised annually with each Framework element updated as needed.

Over the last two years, there have been numerous technical achievements in the HED/ICF portfolio. Record neutron yields have been demonstrated on the National Ignition Facility (NIF) and the Z facility, and record hot spot pressures have been achieved at the OMEGA laser. Innovative ramp compression experiments for diamond at the NIF were highlighted in a cover article in *Nature*. The seventeenth plutonium experiment was executed on Z to study shockless loading at low pressure in order to span the full equation-of-state phase space. The lattice structure of plutonium under extreme pressure and temperature conditions was observed on the NIF. In 2015, researchers at NIF made dramatic improvements in efficiency, exceeding 350 shots in support of stockpile stewardship and, at Rochester, a record 25,000th shot was conducted on the OMEGA laser. New neutron and x-ray sources are being developed to support the qualification of components of stockpile systems in hostile environments for life extension programs.

Today, an unprecedented level of collaboration is occurring in the ICF Program. Scientists from Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), the University of Rochester's Laboratory for Laser Energetics (LLE), and the Naval Research Laboratory (NRL), along with researchers in private industry and academia, are collaborating on diagnostic development, code development, data interpretation and analysis, and facility improvements. For example, LANL, LLNL, SNL, and LLE scientists, together with their academic partners, have established a national working group to study ICF hot spot characteristics at stagnation for all three ignition approaches. SNL, LLNL, General Atomics, and LLE are developing advanced cameras that push the state of the art in order to "make movies" that will enable scientists to explore the evolution of ICF implosions in exquisite detail. LLNL, LLE, SNL, and LANL are developing code capabilities for each site to improve the level of peer review among the laboratories. NRL and LLE regularly conduct experiments using special target design techniques that will reduce implosion instabilities. The productivity and the depth of these collaborations have improved exponentially over the last two years, which will yield many benefits over the coming years.

A comprehensive program review of the HED/ICF portfolio was executed from May to October 2015. Nearly 40 "next steps" were identified that included delivery of eight transformational diagnostics by 2021, doubling the number of Z experiments to support magnetic direct drive by 2019, reprioritizing academic program investments, and developing cross-platform validation capabilities to study the physics of ICF hot spot formation and stagnation.

The ICF Program has developed a goal that, by 2020, we will determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches. The program of work to achieve this goal is described in this Framework document. The ICF Program has also developed Devil's Advocate Red Teams, which are groups of subject matter experts embedded in the ICF Program whose purpose is to challenge the technical assumptions and direction of the Program as it pursues the 2020 goal.

Mission needs for stockpile stewardship are evolving, and the HED/ICF portfolio strives to stay ahead of the need curve. NNSA is evaluating the science and technology needs associated with experimentally probing boost-related physics; developing high-fidelity dynamic materials science platforms for hazardous materials for a number of missions; probing threat-relevant outputs, environments, and effects regimes that may impact nuclear survivability requirements; creating and applying multi-megajoule fusion yields; and training weapons designers and testing their understanding of physics in regimes relevant to secondary performance.

Finally, a special thank you to the Federal and laboratory program leadership who have dedicated months of their lives, thousands of miles of travel, and many nights away from home to bring the Framework together.

This national ICF Program Framework document summarizes the integrated plans and shared goals of the Program for 2016 and subsequent years, as envisioned in the NNSA Laboratory Directors' January 2015 letter to DOE Under Secretary for Nuclear Security Frank G. Klotz. Our efforts over the last 20 months to coordinate national HED/ICF research activities have been fruitful. As delegates of the Laboratory Directors and as the Director of the Laboratory for Laser Energetics, we will continue to work together to ensure HED/ICF efforts remain of high impact to the Nation's Stockpile Stewardship Program.

Charles P. Verdon
Principal Associate Director for Weapons & Complex Integration
Lawrence Livermore National Laboratory

Robert B. Webster
Principal Associate Director of Weapons Program
Los Alamos National Laboratory

J. Stephen Rottler
Deputy Laboratories Director and
Executive Vice President, National Security Programs
Sandia National Laboratories

Robert L. McCrory
Vice President, University of Rochester
Director and CEO
Laboratory for Laser Energetics

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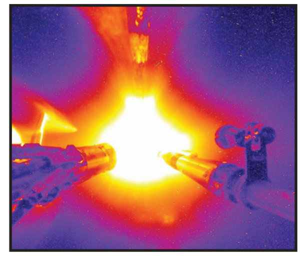

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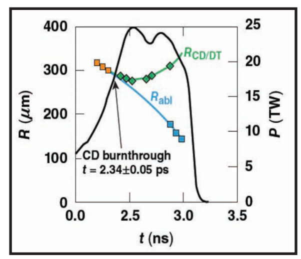

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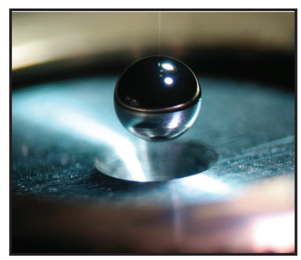

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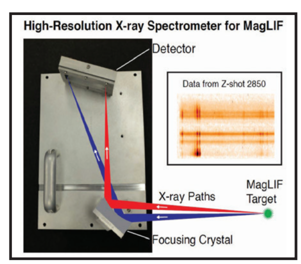

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✧ Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
ARPA-E	Advanced Research Projects Agency-Energy
ARS/X-1	Advanced Radiation Source
Be	beryllium
BR	magnetization
CBET	cross-beam energy transfer
CBI	Curved Backlighting Imager
CCD	charge-coupled device
CCR	case-to-capsule ratio
CEA	Commissariat a l'Energie Atomique
CH	plastic
CR	convergence ratio
D	deuterium
DART	Devil's Advocate Red Team
DOE	Department of Energy
DRACO	University of Rochester's radiation transport code
dsr	down scatter ratio
DT	deuterium-tritium
EOS	equation of state
GA	General Atomics
GCD	gamma spectroscopy
HDC	high-density carbon
HED	high energy density
HEDP	high energy density physics
HEPP	high explosive pulsed power
HYDRA	Lawrence Livermore radiation hydrodynamics code
ICF	inertial confinement fusion, Inertial Confinement Fusion & High Yield (Program)
IEC	Integrated Experimental Campaign
IFH	intermediate fill hohlraum
keV	kilo electron volt
kJ	kilojoule
Kr	krypton
LANL	Los Alamos National Laboratory
LDD	laser direct drive
LID	laser indirect drive
LLE	University of Rochester Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
LPI	laser-plasma instabilities
LPSE	Laser Plasma Simulation Environment
LTE	local thermal equilibrium
MA	megaamperes
MagLIF	Magnetized Liner Inertial Fusion
MCP	micro-channel plate
MDD	magnetic direct drive
MeV	mega electron volt
MIT	Massachusetts Institute of Technology
NDP	National Diagnostics Plan
NDWG	National Diagnostics Working Group
NIF	National Ignition Facility
NIS	Neutron/Gamma Imaging
NISP	National Implosion Stagnation Physics
NLTE	non-local thermal equilibrium
NLUF	National Laser Users' Facility
NNSA	National Nuclear Security Administration
NRL	Naval Research Laboratory
nTOF	neutron time of flight
NTD	neutron temporal diagnostic
OTS	optical Thomson scattering
PDD	polar direct drive
PRD	Priority Research Direction
RDT&E	Research, Development, Test & Evaluation
RKE	Residual Kinetic Energy
SBS	stimulated Brillouin scattering
SLOS	single line of sight
SNL	Sandia National Laboratories
SRS	stimulated Raman scattering
SSAP	Stewardship Science Academic Programs
SSMP	Stockpile Stewardship and Management Plan
SSP	Stockpile Stewardship Program
T	tritium
Ti	ion temperature
TN	thermonuclear
TPD	two-plasmon decay
TRL	Technical Readiness Level
V&V	validation and verification
VISAR	Velocity Interferometer System for Any Reflector
FY	fiscal year
Z	Z Machine

1

Overview

1.1 Background

The Inertial Confinement Fusion and High Yield (ICF) Program supports the mission of the U.S. Department of Energy (DOE)/National Nuclear Security Administration (NNSA) to maintain a safe, secure, and effective nuclear deterrent by creating experimentally diagnosable platforms that access extreme temperature, pressure, and density regimes relevant to nuclear weapons performance. The overwhelming majority of the yield from a nuclear weapon is generated in this high energy density (HED) state. Expertise in HED science is therefore a core technical competency of the Stockpile Stewardship Program (SSP). The ICF Program supports experiments and facilities that generate weapon-relevant HED conditions in specialized laboratory environments, in the absence of nuclear weapons explosive testing. Conducting such experiments requires the development of advanced experimental and computational tools, diagnostics, and technologies such as state-of-the-art laser and pulsed power platforms. The ICF Program collaborates with NNSA's Science Program which sets the programmatic direction for weapons-relevant HED efforts.

"The principal goal of the ICF Program by 2020 is to determine the efficacy of NIF for achieving ignition and the credible physics scaling to multi-megajoule fusion yields for each of the major ICF approaches."

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U.S. nuclear weapons are certified, assessed, and modified by a highly trained workforce, on the basis of simulations and experiments. Models for material properties at extreme pressures, temperatures, and densities inaccessible outside of HED laboratory facilities are used as inputs to simulation tools. Executing successful laboratory experiments exercises the judgment of scientists and engineers, the models they use, and their ability to diagnose thermonuclear (TN) processes relevant to weapons design. The ICF Program contributes to the SSP in the following areas:

- Challenging and developing nuclear weapons designers in HED regimes not otherwise accessible without nuclear weapons explosive testing;
- Validating models for the properties of HED materials used in simulation tools;
- Developing high-fidelity diagnostics, advanced experimental platforms, and predictive capabilities and simulations in HED regimes;
- Creating and applying multi-megajoule fusion yield for assessment of nuclear weapons performance and survivability; and
- Providing opportunities for academic users to push the state of the art in HED science to the mutual benefit of NNSA's mission.

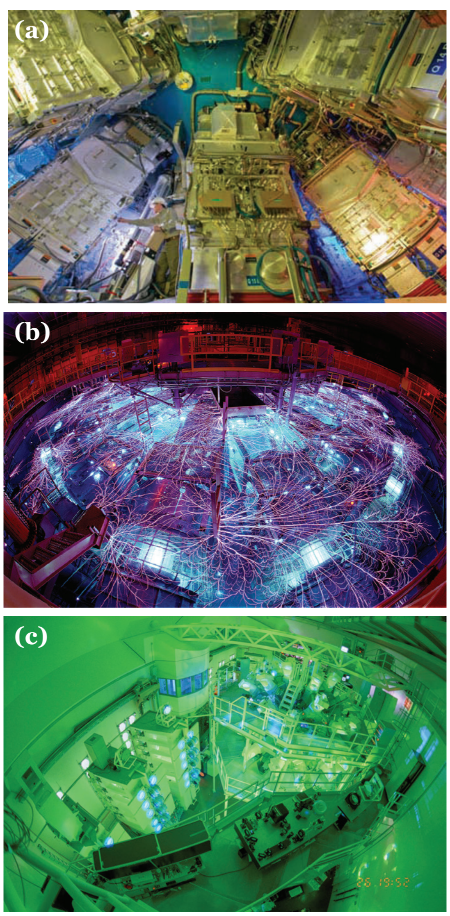

Figure 1-1. (a) The NIF final optics assembly, (b) the Z facility, and (c) the OMEGA laser.

The ICF Program has clear SSP drivers for studying the properties of robust TN burning plasmas, pursuing multi-megajoule fusion yields (which require ignition), and ultimately pursuing high yield. The ICF Program's principal mission since its inception in the early 1960s is to deliver the capabilities and platforms to create and study these conditions. Since the early 1990s, the program has delivered these capabilities in a controlled laboratory environment. Accomplishing that monumental scientific and engineering challenge has required some of the most advanced technologies and facilities ever constructed. Today, the principal goal of the ICF Program by 2020 is to determine the efficacy of the National Ignition Facility (NIF) for achieving ignition and the credible physics scaling to multi-megajoule fusion yields for each of the major ICF approaches.

Most experiments are performed at NNSA's three major HED facilities: the NIF at Lawrence Livermore National Laboratory (LLNL), the Z facility at Sandia National Laboratories (SNL), and the Omega Laser Facility (OMEGA) at the University of Rochester's Laboratory for Laser Energetics (LLE) (see Figure 1-1). The ICF Program includes contributions from the Naval Research

Laboratory (NRL) (see the NIKE laser in Figure 1-2), the Los Alamos National Laboratory (LANL), industry partners in target fabrication (see Figure 1-3), as well as multiple academic institutions supported by the joint program in High Energy Density Laboratory Plasmas with DOE's Office of Fusion Energy Sciences.

1.2 Summary of the ICF Program Framework

To achieve its 2020 goal, the ICF Program has developed an integrated program framework. This framework was principally motivated by four needs.

1. The post-National Ignition Campaign ICF Program needed a clear five-year goal to understand if ignition may be achieved on the NIF (and if not, why not); and, although Z and OMEGA were not built to achieve ignition, these facilities are home to two of the three major approaches to ignition. Therefore, a science program was needed that could explore physics scaling arguments to fusion yield for the approaches and as a means to compare the approaches.
2. The distinction between focused physics experiments and integrated performance experiments needed to be clearly delineated to enable scientific debate regarding the balance between them, given the state of understanding and fixed facility resources.
3. The visibility into program activities needed to be increased to enhance scientific peer review within and among the laboratories, and to subject those activities to healthy criticism from institutions outside of the laboratories in an effort to strengthen the scientific foundation of the ICF Program and the basis for program decision making.
4. Clear milestones, metrics, and deliverables needed to be established that may be achieved for transparency during the intervening years and to track progress.

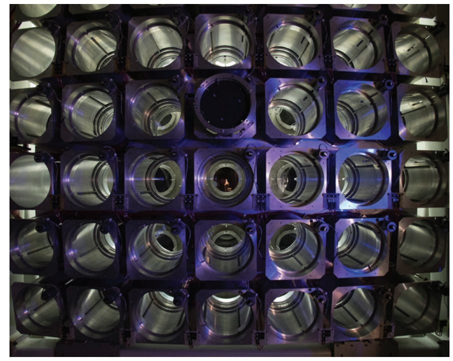

Figure 1-2. The Nike laser focusing array.

The Framework was structured into four major elements:

- ✧ The Ten-Year High Energy Density Science Strategic Plan. This fundamental requirements document outlines the three-, five-, and 10-year deliverables for the HED weapons science portfolio, including the major ICF Program deliverables. Requirements are derived from the annual 25-year Stockpile Stewardship and Management Plan (SSMP) and from the emerging stockpile responsiveness requirements in the National Defense Authorization Act for Fiscal Year 2016.
- ✧ The Integrated Experimental Campaigns (IECs). This element involves an approach-specific set of implosion experiments with the primary objective to baseline performance, demonstrate scaling, test new design features or capabilities, and/or test new target concepts. Performance metrics are highly integrated quantities such as total neutron yield, and milestones are generally spread over multiple years.
- ✧ The Priority Research Directions (PRDs). This element involves fundamental and focused research to develop and improve models, codes, and simulations (i.e., predictive capabilities), and to set detailed, physics-based milestones for experimental research and computational efforts. The PRDs are designed to enable cross-cutting coordination and basic research opportunities for external collaborations.
- ✧ The National Diagnostics Plan. This resource-loaded plan describes a suite of advanced diagnostics to be delivered through 2021 that are cost-shared among LLNL, LANL, SNL, LLE, and NRL. The plan includes contributions from 17 institutions.

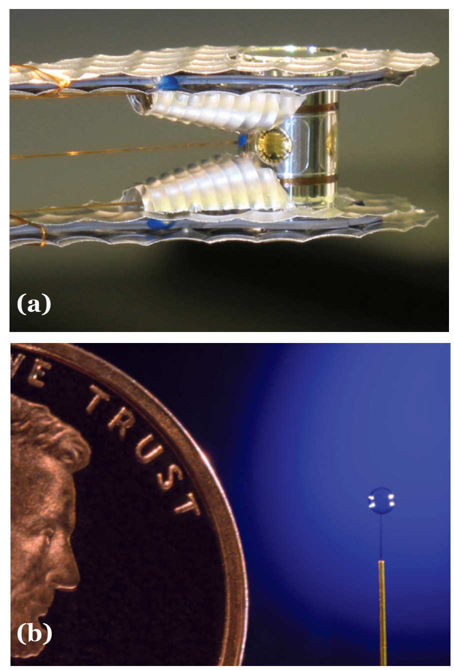

Figure 1-3. (a) A NIF cryogenic ignition target and (b) an OMEGA capsule.

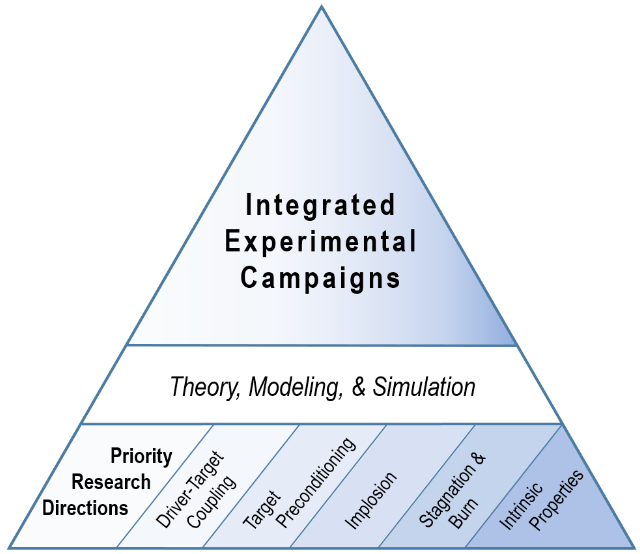

Figure 1-4. The PRDs and the IECs are linked through modeling and simulation. Each is needed to achieve the 2020 ICF Program goal.

Like other activities within the SSP, the focused physics experiments in the PRDs and the integrated performance experiments of the IECs are linked closely through modeling, code, and simulation efforts. First and foremost, the PRDs serve as validation experiments that underpin models in codes that are used for IEC design and performance prediction. IEC experiments also serve as validation experiments. Figure 1-4 shows the relationship between the PRDs and IECs through modeling and simulation.

"The ICF Program Framework is critical to ensuring that our Nation continues to lead and play a vibrant role within the HED community."

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The United States has maintained a strong leadership role in ICF and HED since the development of HED drivers based on megajoule-class lasers and pulsed power. However, the field of research is increasingly international in scope with major facilities built, planned, or under construction worldwide. Notable examples of other major inertial fusion research facilities include the Laser Mégajoule (LMJ) in France, the FIREX Laser in Japan, the SG-III laser and PTS pulsed power facilities in China, the Vulcan and Orion Lasers in the United Kingdom, and numerous smaller facilities in countries such as Russia, India, Poland, the Czech Republic, and Iran. Like the United States, some of these countries are interested in pursuing multi-megajoule fusion yields using approaches similar to those described here. The ICF Program Framework is critical to ensuring that our Nation continues to lead and play a vibrant role within the HED community.

A summary of the major U.S. ICF approaches pursued today is provided in the next section.

1.3 Summary of the Three Major ICF Approaches

The major ICF approaches are:

- Laser Indirect Drive led by LLNL and primarily executed at NIF,
- Laser Direct Drive led by LLE and primarily executed at the OMEGA laser, and
- Magnetic Direct Drive led by SNL and primarily executed at the Z facility.

1.3.1 Overview of Laser Indirect Drive

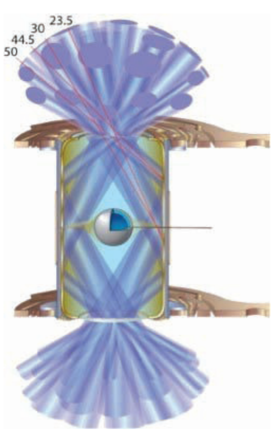

Figure 1-5. The NIF hohlraum converts 192 beams of laser light to x-rays that implode the capsule.

Laser indirect drive (LID), also referred to as laser x-ray drive, is pursued at the NIF. NIF's 192 laser beams inject approximately 1.8 megajoules of laser energy into a cylindrical gold-lined cavity about 1 centimeter long (see Figure 1-5), called a "hohlraum" (German for an empty room). The beams rapidly produce a thermal x-ray source in the hohlraum. The deuterium-tritium (DT) fuel is in a solid layer about the thickness of a human hair on the inside surface of a 2-millimeter-diameter spherical capsule at the hohlraum center. X-rays from the hohlraum vaporize, or ablate, the capsule surface, generating pressures approaching 100 megabars that implode the fuel at nearly 400 kilometers per second. The implosion compresses the fuel by a factor of 30, amplifying the pressure by precision pulse shaping to several hundred gigabars and heating a central "hot spot" of DT. The LID goal is to determine the efficacy of the NIF to achieve ignition and, if this is found to be improbable, to understand the reasons why. Visit https://lasers.llnl.gov/about/what-is-nif for more information.

A goal of LID is to determine the efficacy of the NIF for achieving ignition. Visit https://lasers.llnl.gov/about/what-is-nif for more information.

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1.3.2 Overview of Laser Direct Drive

Laser direct drive (LDD) couples the laser energy directly to the capsule surface. OMEGA has 60 symmetrically arranged beams that focus up to 30 kilojoules on the capsule to produce symmetric implosions (see Figure 1-6). Tailoring the laser profile generates up to 140 megabar pressures at the capsule surface. The primary LDD challenge is ensuring each laser beam is sufficiently smooth (i.e., the intensity variation across the beam is small) and the number of beams is sufficient to minimize nonuniformities caused by beam overlap. Beam smoothing techniques developed over the past two decades at LLE have ensured the drive uniformity rivals that with x-ray drive in a hohlraum. Tailoring the laser intensity temporal profile reduces the growth rate of perturbations at the ablating capsule surface. Because LDD is predicted to couple 5-10 times more energy into the hot spot than LID (for the same incident laser energy), the fuel mass can be increased, reducing the ignition threshold hot spot pressure by roughly a factor of three to 120-140 gigabars. LDD ignition is predicted to occur at fuel compressions of 22-25. Maximizing the energy absorption in the target and thus the imploded mass is a major LDD goal. The OMEGA laser was not designed to achieve ignition, but LDD research at sub-scale will inform decisions regarding the path to ignition. Visit http://www.lle.rochester.edu/directorsoffice.php for more information.

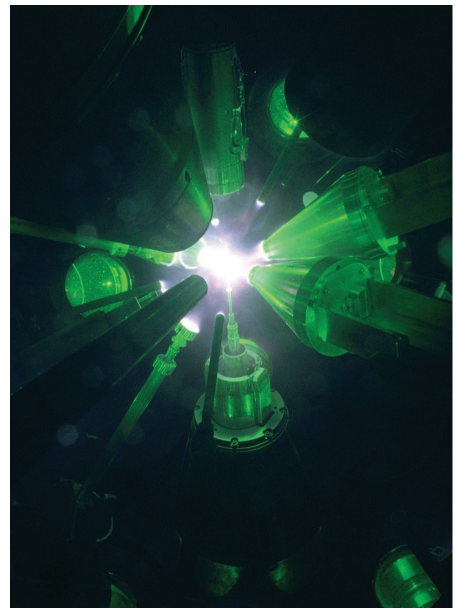

Figure 1-6. A cryogenic DT implosion inside the 60-beam OMEGA target chamber at LLE, where most LDD-relevant research is conducted.

1.3.3 Overview of Magnetic Direct Drive

Magnetic direct drive (MDD) refers to using large electrical currents, and the resulting magnetic field, to compress the fuel directly to the conditions for fusion. The primary facility for studying this approach is the Z pulsed power facility at SNL. Z stores approximately 20 megajoules in its capacitor banks. That energy is compressed in space and time to produce a peak current of up to 26 megaamperes. This large current is passed through a cylindrical liner containing the DT fuel that creates a strong magnetic field and results in a radially inward force that compresses and heats the DT (see Figure 1-7). Prior to the compression, a laser heats a thin column of the fuel and a seed magnetic field is added, reducing heat conduction losses from the laser-heated fuel during the compression. Calculations suggest that when certain conditions are satisfied, charged particles produced by the DT reactions

A goal for LDD is to demonstrate greater than 100-gigabar hot-spot pressure on OMEGA. Visit www.lle.rochester.edu for more information.

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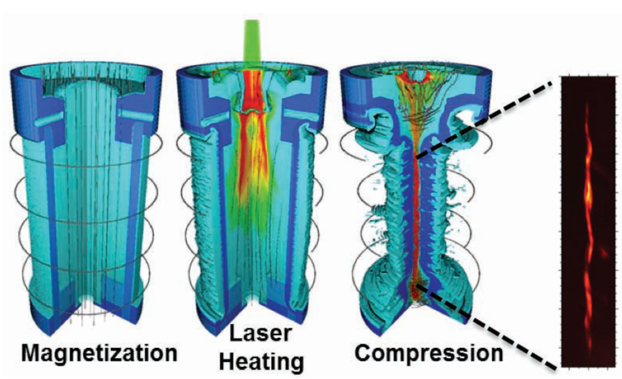

Figure 1-7. The liner on Z is roughly the size of a thimble. The goal of the MDD effort is to radiate 100-kilojoule DT-equivalent neutrons from this target.

heat the fuel further and are confined to helical orbits, reducing the fuel compression requirements. The goal is to demonstrate 100-kilojoule (kJ) DT equivalent yields on Z. The Z was not designed to achieve ignition, but MDD research at sub-scale will inform decisions regarding the path to ignition. Visit http://www.sandia.gov/Pulsed-Power/res-areas/inertialconfinement/index.html for more information.

A goal of MDD is to demonstrate 100-kilojoule DT equivalent yields on Z. Visit http://www.sandia.gov/Pulsed-Power/res-areas/inertialconfinement/index.html for more information.

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1.3.4 Overview of Target Fabrication Activities

Every HED experiment for ICF requires a specialized "target," the physical experimental package that is under investigation (see Figure 1-8). The energy delivered to a target can create temperatures greater than the core of the Sun and pressures greater than the core of the Earth to allow scientists to study the physics of HED plasmas. Many ICF target experiments require hydrogen fuel to be frozen at 20 degrees Kelvin to achieve the high fuel densities after compression needed for ignition, TN burn, and high fusion energy gain. Targets and target components are primarily supplied by two industry partners, General Atomics (GA), http://www.ga.com/ift-role and Schafer Corporation, http://www.schafercorp.com/laboratories/livermore/. NNSA also provides support to industry partners and the development and fabrication of the engineering systems for filling, transport, and the insertion of cryogenic targets.

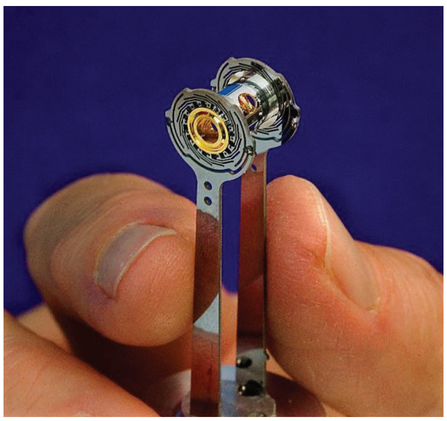

Figure 1-8. A NIF hohlraum target.

1.4 Framework Document Summary

This document summarizes the key components of the ICF Program Framework. It emphasizes the technical program to achieve robust TN burning plasmas in the laboratory. Facility operations, governance, and the details of the support of other stockpile stewardship activities are covered in other program management documents.

The primary audience for this document is three distinct groups, all with familiarity of the scientific mission of the ICF Program. First, the document is for the hundreds of scientists, engineers, and technicians—the stockpile stewards—who work every day on perhaps one approach or aspect of the ICF Program, but maintain a technical interest or may have something to contribute to another aspect to the program into which they presently have no visibility. Second, it is for the laboratory and Federal leadership and management: (a) to agree on the priorities and plans for the coming years, and (b) to gain an appreciation of the technical challenges and the breath of activities across the ICF Program. Third, and quite importantly, the document is for external stakeholders (e.g., Congress, Department of Defense, academia, etc.) to see that the comprehensive management structure of today's ICF Program has clear deliverables, milestones, and metrics and that the Framework enables the ICF Program to set priorities for future investments.

This document summarizes the key components of the ICF Program Framework as compared to more comprehensive documentation of requirements and plans.

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The Framework document will be updated annually. ICF Program leadership is working several additional program areas in anticipation of next year's update. These include: 1) next generation computer codes tailored to plasma and HED environments that fully utilize evolving computer architectures; 2) extension of national Working Groups into other technical areas such as laser-plasma interactions; 3) assessing the worldwide ICF landscape and understanding international competitiveness; 4) establishment of "traineeships" in specific fields of critical importance such as atomic physics and spectroscopy; and 5) conceptualizing a laboratory basic science program for the NIF and Z.

The Ten-Year High Energy Density Science Strategic Plan

2

2.1 Background

From the *U.S. Department of Energy Strategic Plan 2014-2018, March 2014 (page 13)*

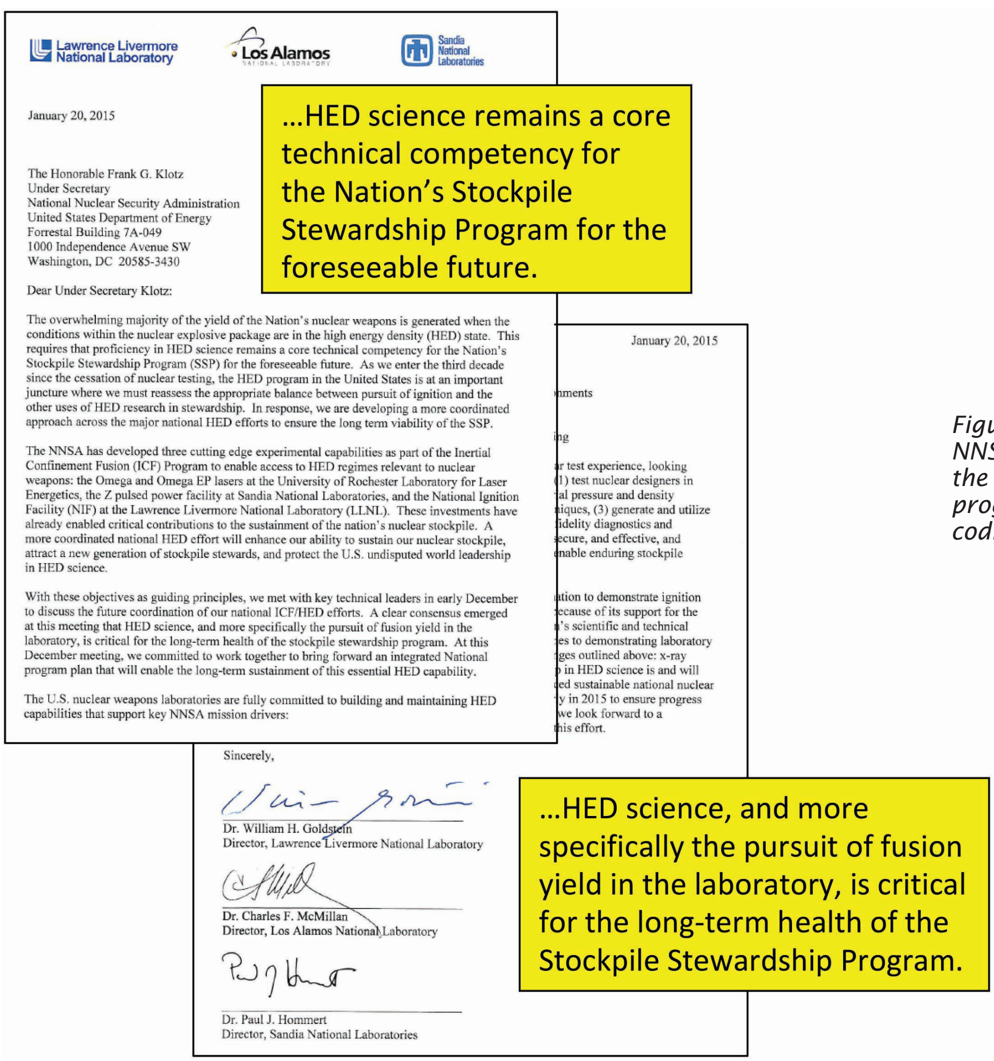
Goal 2: Nuclear Security
Strengthen national security by maintaining and modernizing the nuclear stockpile and nuclear security infrastructure, reducing global nuclear threats, providing for nuclear propulsion, improving physical and cybersecurity, and strengthening key science, technology, and engineering capabilities

Strategic Objective 4 – Maintain the safety, security and effectiveness of the nation's nuclear deterrent without nuclear testing

The U.S. Department of Energy's *2014-2018 Strategic Plan* (March 2014) cites a strategic objective to maintain the safety, security, and effectiveness of the Nation's nuclear deterrent without nuclear testing. NNSA's Defense Programs support this objective by performing experimental and theoretical research in the HED regime, which reaches the most extreme conditions possible in the laboratory. This research and the associated facilities are supported by the ICF and Science Programs within NNSA's Research, Development, Test, and Evaluation (RDT&E) portfolio.

In December 2014, the three NNSA Laboratory Directors, senior staff of the laboratories, and the LLE leadership defined decadal mission drivers for the HED/ICF program in support of the SSP. The Directors codified these mission drivers in a January 2015 letter to the DOE Under Secretary for Nuclear Security (see Figure 2-1). These five mission drivers are:

- Test weapon designers in HED experimental design;
- Access material pressure and density regimes that are inaccessible via other experimental techniques;
- Generate and use TN burning plasmas;
- Develop commensurate high-fidelity diagnostics and experimental platforms; and
- Create and apply multi-megajoule fusion yields.



January 20, 2015

The Honorable Frank G. Klotz
Under Secretary
National Nuclear Security Administration
United States Department of Energy
Forrestal Building 7A-049
1000 Independence Avenue SW
Washington, DC 20585-3430

Dear Under Secretary Klotz:

The overwhelming majority of the yield of the Nation's nuclear weapons is generated when the conditions within the nuclear explosive package are in the high energy density (HED) state. This requires that proficiency in HED science remains a core technical competency for the Nation's Stockpile Stewardship Program (SSP) for the foreseeable future. As we enter the third decade since the cessation of nuclear testing, the HED program in the United States is at an important juncture where we must reassess the appropriate balance between pursuit of ignition and the other uses of HED research in stewardship. In response, we are developing a more coordinated approach across the major national HED efforts to ensure the long term viability of the SSP.

The NNSA has developed three cutting edge experimental capabilities as part of the Inertial Confinement Fusion (ICF) Program to enable access to HED regimes relevant to nuclear weapons: the Omega and Omega EP lasers at the University of Rochester Laboratory for Laser Energetics, the Z pulsed power facility at Sandia National Laboratories, and the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL). These investments have already enabled critical contributions to the sustainment of the nation's nuclear stockpile. A more coordinated national HED effort will enhance our ability to sustain our nuclear stockpile, attract a new generation of stockpile stewards, and protect the U.S. undisputed world leadership in HED science.

With these objectives as guiding principles, we met with key technical leaders in early December to discuss the future coordination of our national ICF/HED efforts. A clear consensus emerged at this meeting that HED science, and more specifically the pursuit of fusion yield in the laboratory, is critical for the long-term health of the stockpile stewardship program. At this December meeting, we committed to work together to bring forward an integrated National program plan that will enable the long-term sustainment of this essential HED capability.

The U.S. nuclear weapons laboratories are fully committed to building and maintaining HED capabilities that support key NNSA mission drivers:

January 20, 2015

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ges outlined above: x-ray
in HED science is and will
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y in 2015 to ensure progress
we look forward to a
his effort.

Sincerely,

Dr. William H. Goldstein
Director, Lawrence Livermore National Laboratory

Dr. Charles F. McMillan
Director, Los Alamos National Laboratory

Dr. Paul J. Hommert
Director, Sandia National Laboratories

Figure 2-1. Letter signed by the three NNSA Laboratory Directors in which the mission drivers for the HED/ICF program in support of the SSP are codified.

With these mission drivers in mind, a 10-year HED Science Strategic Plan was developed (National HED Strategy (U)," Document No. LLNL COPD-2015-0003, LANL LA-CP-15-00064, January 2015). The plan is inherently a key requirements driver for the ICF Program Framework. The ICF Program mission drivers are derived from the SSP needs captured in the HED Science Strategic Plan, particularly in the Thermonuclear section of that Plan. In addition, the broader HED weapons science portfolio relies on the ICF Program to produce HED environments through its world-class facilities and experimental capabilities such as advanced target designs, diagnostics, and facility operations.

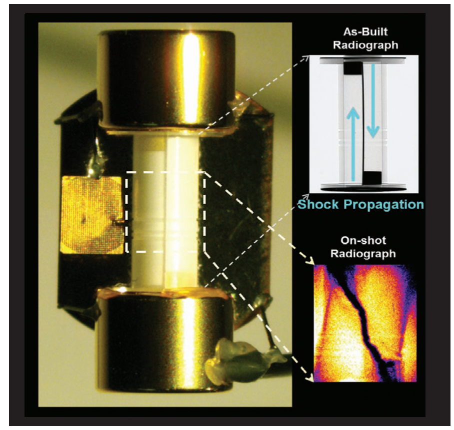

Figure 2-2. A LANL experiment depicting an interface that has been shocked and sheared to study mix.

2.2 Key Technical Focus Areas

The HED strategic plan consists of four key weapons physics areas aimed at replacing empirical models with experimentally-validated models in weapons codes: nuclear; TN; radiation transport; and outputs, environments, and effects. The HED portfolio must support specific assessment capabilities that increase the design options of life-extended weapons by replacing components and materials, adjusting to changes in manufacturing processes, improving safety and surety, and meeting vulnerability and hardness requirements. Thermonuclear aspects of nuclear weapon performance are a focus of major HED future efforts. This focus will require TN burn capabilities of varying yields (100 kilojoules through multi-megajoules) that are being developed by the ICF Program.

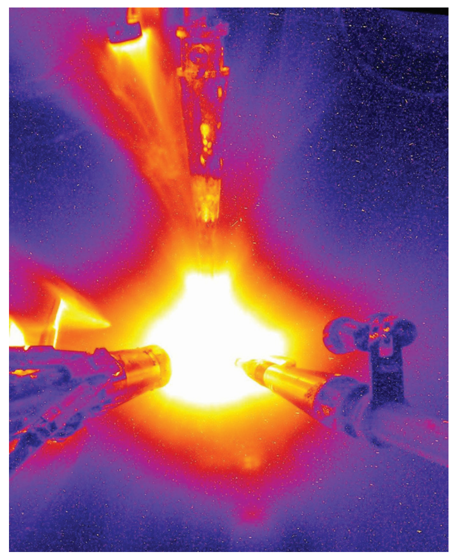

Figure 2-3. NIF 'Bigfoot' experiment.

2.2.1 Nuclear

The nuclear HED area is advancing understanding of the implosion phase of a nuclear weapon. Major physics topics in this area include hydrodynamics, material properties under extreme conditions, and nuclear physics. Hydrodynamics in the nuclear phase is complex and has a profound impact on nuclear weapon performance. Stability of implosions and turbulence are fundamental to address, concerning the hydrodynamics in a plasma media. Figure 2-2 shows data from a NIF experiment demonstrating a mixing layer structure under HED conditions. Hydrodynamic evolution is strongly dependent on material properties and external conditions, such as the presence of strong magnetic fields. HED experiments provide precision data on material properties at stockpile relevant conditions, such as TN (equations of state (EOSs)), material phase, and strength.

2.2.2 Thermonuclear

Thermonuclear reactions reach very high temperatures and densities, similar to those at the center of stars, supernovae, and nuclear weapons. Validated models of the energy production from fusion reactions are needed to understand weapon performance, including primary boost and secondary performance. HED experiments at the three major ICF facilities can contribute to understanding the interplay of TN physics and other physical phenomena through the development of burning plasma platforms.

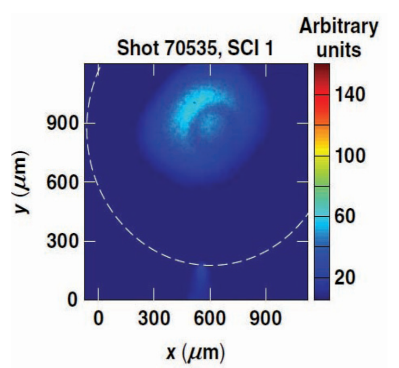

Figure 2-4. An in-flight soft x-ray radiograph of a low adiabat (a ~ 2.5) cryogenic DT implosion on OMEGA taken 200-300 ps before bang time. The white dashed line is the original capsule radius and the dark circle (centered on x ~ 600 mm and y ~ 900 mm) is the in-flight DT shell.

The primary mission of the ICF Program is to focus on developing a robust TN burn platform and achieving multi-megajoule fusion yields (which require ignition) and, ultimately, a high yield platform. The ICF Program is developing a burning plasma platform using three approaches: LID (Figure 2-3 shows an open shutter colorized NIF implosion inside the target chamber), LDD (Figure 2-4 shows a direct-drive cryogenic DT experiment on OMEGA), and MDD (Figure 2-5 shows a Magnetized Liner Inertial Fusion (MagLIF) target, implosion radiograph, and an x-ray image at stagnation).

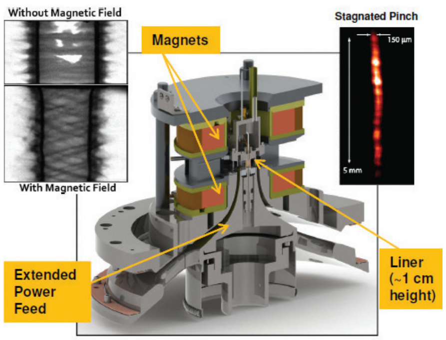

Figure 2-5. A MagLIF target.

Planned experiments on ignition and on applications of ignition include a broad range of areas related to TN performance. Data from precisely-diagnosed burn experiments will help to elucidate the physics that must be incorporated in sophisticated nuclear weapon simulation codes to assess and certify options for the life extension programs of the Nation's nuclear weapons. These experiments will advance and validate physics models and numerical simulation codes and will serve as integrated tests of simulation capabilities. The conditions of ignition create very hot, dense radiative plasmas with high neutron flux. Burn and ignition physics experiments will address issues related to TN reactions in deuterium (D) and tritium (T) as well as other nuclear physics issues in a high neutron flux environment. This unique environment will allow validation of physics-based models and numerical simulation codes; assessment of weapon performance; and evaluation of output, environment, and effects. Moreover, advances in the understanding of specific aspects of TN burn physics will inform the assessment of stockpile aging issues of current interest and contribute to broader national security concerns.

2.2.3 Radiation Transport

Radiation transport research examines the propagation of x-rays and their interactions with materials. HED efforts measure radiation propagation in relevant geometries to validate the algorithms in weapon design codes and obtain data to validate opacity models that govern the absorption and transmission of x-rays in nuclear devices. Figure 2-6 depicts a NIF target used to study radiation transport. First-principles simulations of opacities are beyond the scope of current supercomputers. Instead, opacity models use approximate methods with uncertainties that are difficult to quantify in large-scale computer simulations. Experiments being conducted on Z and the NIF are important for improving opacity theory and models, but are restricted to lower temperatures and densities than those attained in nuclear weapon explosions.

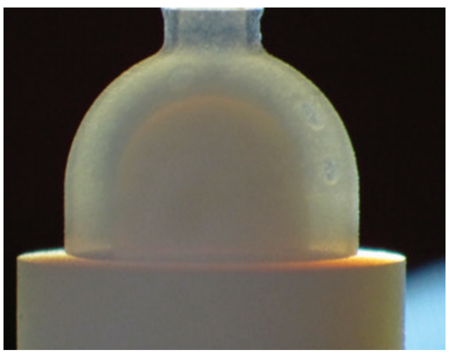

Figure 2-6. A typical NIF radiation transport target.

2.2.4 Outputs, Environments, and Effects

Outputs, environments, and effects research (see Figure 2-7) focuses on the post-explosion phase, in which the nuclear weapon releases x-rays, neutrons, gammas, and blast waves that deliver a militarily effective response to an intended target. Studying the physics of outputs and effects allows an assessment of the intended and unintended consequences of weapon explosion. This includes understanding the radiation output from U.S. systems and adversaries' systems, the response of U.S. systems to hostile environments generated by a nuclear-tipped interceptor or a fratricide scenario, and extreme environments such as the electromagnetic pulses that nuclear weapons may create. HED facilities contribute to understanding these scenarios and to supporting the qualification of components of U.S. systems to meet nuclear survivability requirements. Many investigations in this area require new experimental and computational capabilities to explore the effects of large neutron and x-ray outputs.

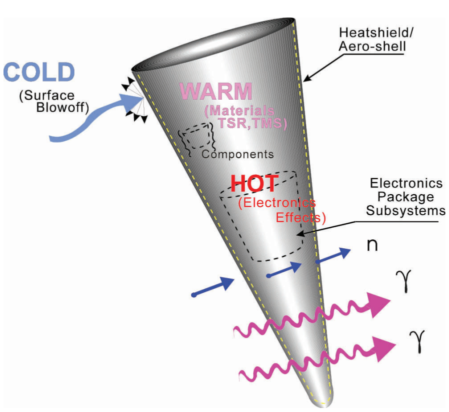

Figure 2-7. Typical environments that HED capabilities are used to simulate.

2.3 Summary

The capability to measure, model, and simulate conditions in the HED regime is critical to the SSP. As stated by the Laboratory Directors in their letter to the NNSA Administrator, "Continued leadership in HED Science is and will continue to be an essential component of a coordinated and balanced sustainable national nuclear security enterprise." The ICF Program vision is to deliver the HED science and capabilities to support the evolving nuclear stockpile. The motivations for these efforts include stockpile changes observed since the cessation of underground nuclear testing, weapon-performance sensitivity studies, and uncertainty-quantification analyses. Aligned with the anticipated needs of future stockpile decisions, the resolution of nuclear and TN uncertainties in the coming decade is the priority of HED research. This will require the development of robust burning plasma platforms. NNSA efforts to understand outputs and their interactions with the environment will gradually increase. Efforts to understand radiation transport will gradually lessen as key issues in this area are resolved.

In the absence of underground nuclear explosive testing, it is critical that the NNSA have a means to sustain an expert workforce that can respond to both the anticipated and unanticipated future needs of the Nation's stockpile. The ICF Program, in addition to the highly successful Stewardship Science Academic Programs (see *Developing the Next Generation: The Stewardship Science Academic Programs* on page 12 to learn more), has been effective in recruiting and retaining the best and brightest future stewards, and in challenging them with hard problems. Conducting HED experiments and achieving ignition in the laboratory, in particular, are extremely complex and challenging problems. Weapons designers and experimentalists must exercise the full range of modern SSP computational and experimental capabilities to achieve these goals and demonstrate to allies and adversaries that the U.S. nuclear deterrent remains safe, secure, and effective and that we have the capabilities necessary to assess intelligence-based nuclear threats when they arise.

The ICF Program has been effective in recruiting and retaining the best and brightest future stewards, and in challenging them with hard problems. Conducting HED experiments and achieving ignition in the laboratory, in particular, are extremely complex and challenging problems.

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Developing the Next Generation
Stewardship Science Academic Programs

The Nation's nuclear weapons stockpile is a vital part of the national security infrastructure. Ensuring that the deterrent is second to none requires the best science and technology, especially in the post-nuclear testing era. Having top-tier scientists and engineers in areas critical to stockpile stewardship is the only way to ensure the delivery of the best science and technology possible. The NNSA supports this effort through the Office of Research, Development, Test, and Evaluation's Stewardship Science Academic Programs (SSAP).

The first objective of the SSAP is to support and train doctoral and master's degree science and engineering students to serve as potential stewards of the stockpile. A second objective is to engage highly-skilled academic and NNSA scientists in the development of new ideas and techniques applicable to stockpile stewardship. A third objective is to ensure a strong community of technical experts throughout the country, external to the national security laboratories, to provide peer review, scientific competition, and depth and breadth in research fields essential to NNSA's mission.

The ICF Program benefits substantially from the following SSAP elements.

- The Stewardship Science Academic Alliances (SSAA) Program funds fundamental research and development through Centers of Excellence, research grants, and fellowships in dynamic materials properties, hydrodynamics, low energy nuclear science, radiochemistry, and high energy density physics.
- The High Energy Density Laboratory Plasmas (HEDLP) Program is jointly conducted by NNSA's Office of Inertial Confinement Fusion and DOE's Office of Fusion Energy Sciences. HEDLP funds grants to study plasma in laboratory experiments, where the stored energy reaches approximately 100 gigajoules per cubic meter (i.e., at pressures of approximately 1 megabar). Some areas of interest include HED hydrodynamics, radiation-dominated hydrodynamics, material properties, nonlinear optics of plasmas, laser plasma interactions, and warm dense matter.
- The National Laser Users' Facility (NLUF) Program provides facility time on the Omega Laser Facility. Through this program, two of the world's premier lasers for high energy density research, OMEGA and OMEGA EP, are accessible to the academic and industrial community to conduct basic research experiments in low and high energy density physics and laser-matter interactions and to provide the experience for a cadre of highly-trained scientists to conduct state-of-the-art research in these areas of science and technology.

NNSA Stewardship Science Graduate Fellowship Class of 2015. Left to right: Nathan Finney, Columbia University; Christopher Miller, Georgia Institute of Technology; Brooklyn Noble, University of Utah; Amy Lovell, Michigan State University; Leo Kirsch, University of California (UC) Berkeley, and Alison Saunders, UC Berkeley.

Integrated Experimental Campaigns

3

The Integrated Experimental Campaigns (IECs) constitute a major body of work totaling nearly half of all ICF experiments conducted at the major facilities. The IECs are an approach-specific set of implosion experiments whose primary objective is to baseline the target performance, demonstrate scaling, test new design features and capabilities, and evaluate new ICF target concepts. Performance metrics are highly integrated quantities such as total neutron yield, and most objectives and milestones of the IECs are multi-year. The 2020 goal of each of the three approaches (LID, LDD, and MDD) is to determine the credible physics scaling to multi-megajoule fusion yields using existing facilities, with LID also determining the efficacy of NIF for achieving ignition. Each section below contains a description of the major IECs and a five-year schedule to achieve the 2020 goal.

Table 3-1 depicts a summary of the major phases for each approach toward the 2020 goal. Section 6 presents the peer-review process that will be used to ensure that the body of work being executed will, in fact, achieve the 2020 goal.

3.1 Laser Indirect Drive

3.1.1 Phases of the Laser Indirect Drive IECs

The major deliverables for the five-year IECs are motivated by performance discrepancies between one-dimensional (1D) predictions of NIF implosion performance and measured performance. Figure 3-1 depicts a comparison between the two. Understanding and replicating near-1D performance on the NIF as a function of laser energy is the principal motivation for the IECs.

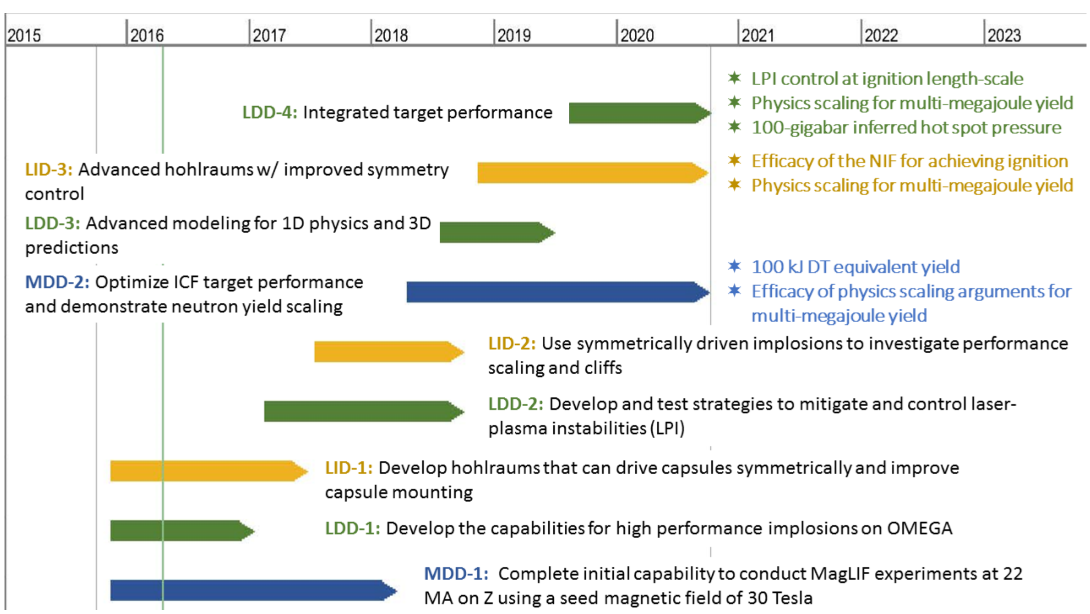
The IECs are an approach-specific set of implosion experiments whose primary objective is to baseline the target performance, demonstrate scaling, test new design features and capabilities, and evaluate new ICF target concepts.

The 2020 goal is to: 1) demonstrate the efficacy of the NIF for achieving ignition and, if unable to do so, understand why, and 2) demonstrate the efficacy of physics scaling arguments for multi-megajoule fusion yield. During each phase, focused physics experiments will be performed to complement the IECs with the goal of understanding and providing data to develop and validate predictive models (see Section 4.1). The combination of integrated and focused experiments, coupled with predictive models, will form the basis for evaluating progress toward the 2020 goal.

3.1.1.1 Phase 1 (FY 2016-FY 2017)

The major focus of Phase 1 is to address two issues that appear to limit capsule performance:

Table 3-1. Summary of the Three Approaches to Achieve the 2020 Goal.



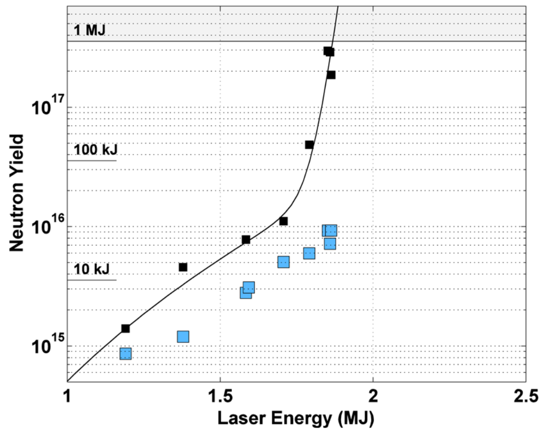


Figure 3-1. Project 1D performance as a function of laser energy (black squares) and measured performance of NIF implosions (blue squares).

- time-dependent drive asymmetry of hohlraums dominated by laser-plasma instabilities (LPI), and
- capsule support membranes that introduce capsule shell ruptures during the implosion.

Both effects prevent efficient energy transfer to the hot spot and degrade confinement. The goal is to develop symmetrically-driven implosions, with reduced impact from the capsule support membranes, for subsequent studies of capsule physics and target scaling. During this period, low-density gas-filled hohlraums with low levels of LPI will be used to develop symmetrically-driven capsules. In parallel, new capsule mounting schemes will be developed and tested in integrated implosions to reduce the impact on the implosion. This goal is to provide a foundation for understanding stagnation in a nearly 1D environment and for exploring hohlraum and capsule performance scaling and cliffs as the targets are pushed in more stressing directions.

The five-year IECs for LID will be executed in three phases.

- *Phase 1. Develop hohlraums that can drive capsules symmetrically and improve capsule mounting.*
- *Phase 2. Use symmetrically driven implosions to investigate performance scaling and cliffs.*
- *Phase 3. Introduce advanced hohlraums that exhibit improved symmetry control.*

3.1.1.2 Phase 2 (FY 2017-FY 2018)

During Phase 2, the new target designs developed in Phase 1 will be used to determine the target scaling and performance cliffs. Specific Phase 2 activities will include:

- Gradually increase the capsule velocity by combining higher laser power and energy with thinner capsules until a performance limit or cliff is reached. This limit may be caused by a combination of reaching NIF's power and energy limits, loss of drive symmetry, or loss of capsule integrity due to hydrodynamic instabilities.
- Reduce the case-to-capsule ratio (CCR), which is the hohlraum radius divided by the capsule radius, until symmetry control is lost.
- Change the physical scale of the target at fixed CCR.
- Conduct comparative studies of capsules with an outer layer (called an "ablator") of CH (plastic), high density carbon (HDC), or beryllium (Be).

Phase 2 will establish the performance limits of NIF capsule implosions in simple cylindrical hohlraums with low LPI and enable the down select of the ablator capsule material.

3.1.1.3 Phase 3 (FY 2019-FY 2020)

The Phase 3 goal is to introduce more advanced hohlraums that exhibit improved symmetry control. Possible designs include hohlraums with low-density foam liners coupled with alternative geometries. Low-density foam liners in simple cylindrical hohlraums should substantially improve the symmetry control. Other advantages could include longer laser pulses and smaller CCRs. The studies in Phase 2 will be repeated for these improved hohlraums, using the most promising designs.

3.1.2 Detailed 2016 Activities

The major goal of the 2016 IECs is to establish the operable parameter space and drive strategy for ignition-relevant implosions for low LPI hohlraums, which have improved symmetry control.

Integrated experiments planned for FY 2016 are shown in Figure 3-2, which spans both hohlraum and capsule stability risk while building on existing data as much as possible. The goal is to identify the parameter space below the notional dashed curve in which the hohlraum is well behaved and good symmetry control can be obtained as a starting point for follow-on studies. The parameter space is the ratio of hohlraum diameter to capsule diameter or CCR, and laser pulse length that relates to capsule convergence ratio (CR) and therefore to the potential 1D target gain for each ablator. Hohlraum gas fill, detailed pulse shape, and laser pointing add degrees of control for drive symmetry.

The IECs planned for 2016 for LID are depicted schematically in Figure 3-2 and listed in Table 3-2 at the end of this section.

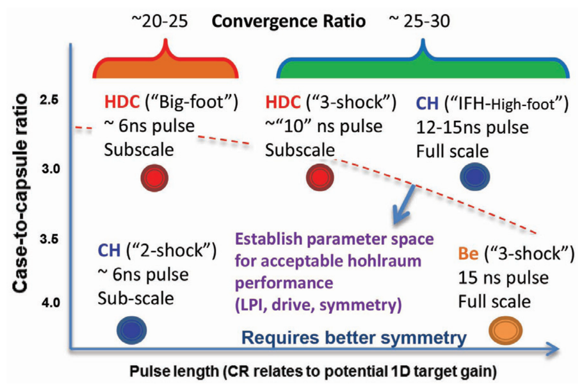


Figure 3-2. The LID integrated experiments are exploring the parameter space of CCR and pulse length to optimize performance. Different ablators (e.g., plastic, high density carbon, and Be are used to explore the parameter space.

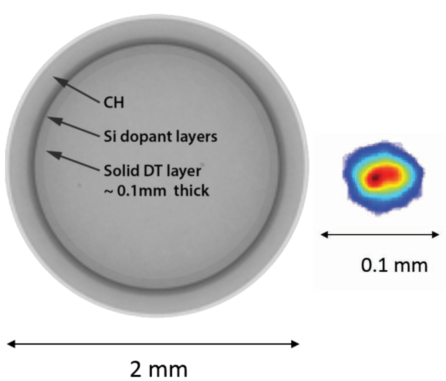


Figure 3-3. (Left) X-ray of a plastic cryogenic NIF capsule containing a solid layer of DT fuel prior to a shot. (Right) False color x-ray image of the DT "hot spot" that forms after a similar capsule was imploded on NIF experiment N140520 which produced 9.3×10^{15} neutrons. The DT in the hot spot has a temperature of approximately 50 million degrees (more than four times that at the center of the sun) and a density estimated to be 50 g/cc (about 1/3 that at the center of the sun or 50 times that of liquid water). It is estimated that alpha particle self-heating amplified the neutron yield by roughly a factor of two in this experiment.

Bigfoot

Bigfoot is a campaign that will evaluate the use of a short laser pulse that causes a low convergence (low gain) compression of an HDC ablator target in a hohlraum. It will also test a design that is different from that of the conventional hot spot design. Bigfoot aims to implode the HDC capsule to a convergence ratio ~ 20, such that the entire DT payload forms a large (ρR ~ 0.5g/cm2), high-temperature hot spot. Bigfoot does this by imploding the capsule at high velocity (> 400 km/s), but on a high adiabat for stability. The design begins with a thin DT payload and three shocks deliberately mistimed to put the DT payload on a high adiabat. This design has the added advantage that the pulse is relatively short (~ 6 ns). Once the drive and the symmetry have been adequately controlled and the implosion behavior is understood, the fuel adiabat can be decreased in subsequent implosions by gradually thickening the cryogenic DT layer (see Figure 3-3 for a generic description of a layered NIF target), while leaving the pulse, and hence the hohlraum drive and symmetry, unchanged. The capsule performance can then be studied as the convergence ratio is gradually increased. Eventually, additional pulse shaping would be required to achieve even higher convergence ratios and would naturally move towards the regular high-convergence, longer-pulse HDC design.

FY 2016 goal: Complete initial experiments in 0.8 scale, CCR ~ 3 hohlraums to provide hohlraum drive and symmetry characteristics for short pulses. Evaluate the efficacy of the Bigfoot design for ignition to provide a symmetric implosion for stagnation physics studies.

High Density Carbon (HDC)

This long-pulse companion (high gain end) of the Bigfoot design uses the same hohlraum size and gas fill to continue to explore a standard, three-shock ($\alpha \sim 2$), high-convergence design (~ 30) at a 0.8 radius scaling. Experiments with a low-convergence (~ 20) gas-filled capsule have exhibited low LPI and good symmetry control by laser pulse shaping techniques.

FY 2016 goal: Determine whether there is a path to a hohlraum that supports a symmetric, three-shock, low-adiabat HDC design in a hohlraum with CCR ~ 3.

Two-shock

Two-shock experiments have used a conservative design with a CH capsule and a CCR ~ 4. Experiments in near-vacuum or low-fill hohlraums and gas-filled capsules with convergence ratios up to ~ 17 have exhibited low LPI and very round implosions. Testing this apparently high-quality hohlraum environment at higher convergence with a DT-layered capsule requires a new, thinner capsule with a different inner radius but the same outer radius to preserve the pulse length, hohlraum drive, and symmetry. Surrogate experiments will be needed to quantify aspects such as shock timing.

FY 2016 goal: Conduct initial surrogate experiments leading up to an evaluation of initial symmetry and performance for a DT-layered capsule with convergence ratio ~ 20-27.

CH Ablator with Intermediate Fill Hohlraum (IFH)

The goal of this effort is to test the hypothesis that time-dependent drive asymmetry is a major factor limiting the performance of a high foot implosion with a CH ablator. The CH intermediate-gas-fill hohlraum experiments will also establish the hohlraum LPI, drive, and symmetry sensitivity to the gas fill, pulse length, and foot pulse level within the same design. These trends in sensitivity should be similar to other low-fill hohlraum designs even if quantitatively different. Experiments will be performed with a larger (6.72-mm-diameter) hohlraum, beginning with intermediate gas fill (~ 0.6 g/cc) and using laser pulses that emulate the radiation temperature history of the original high foot experiments with a CH ablator to isolate the hohlraum physics. The capsule will remain the same size as in the high foot implosions, resulting in a CCR ~ 3 compared to ~ 2.5 for the LPI-dominated, 1.6-mg/cc, He-filled hohlraum used for the high foot experiments. The pulse lengths vary from ~ 10-15 ns for the IFH target design.

FY 2016 goal: Explore laser pulse shape and gas fill to guide design parameters (CCR, pulse shape, gas fill) for symmetric implosion in a low-LPI hohlraum.

Beryllium Ablator with Large Case-to-Capsule Ratio

A Be ablator is predicted to be more hydrodynamically stable than CH or HDC; hence, Be could reduce the effects of fill tubes and capsule mounts or improve symmetry by enabling a larger hohlraum CCR with a lower associated drive temperature.

FY 2016 goal: Conduct initial experiments using Be capsules in CCR ~ 4 hohlraums with the gas fill, laser pointing, and pulse shape optimized for Be capsules.

Wetted Foams

Wetted foams offer the attractive possibility of allowing variation in the capsule convergence ratio over a wide range by adjusting the central DT vapor density while leaving the laser pulse unchanged. The experiments will use developments in other concepts to guide the shape of the laser pulses and the hohlraum design.

FY 2016 goal: Conduct initial experiments using wetted foam capsules.

✧ **Key**
Be - Beryllium
CCR - Case-to-capsule ratio
CR - Convergence ratio
HDC - High density carbon
IFH - Intermediate fill hohlraum
LPI - Laser-plasma instabilities
mm - Millimeters
MJ - Megajoules
ns - Nanoseconds

Table 3-2. Six Integrated Experimental Designs That Will Be Examined to Develop Operable Parameter Space and Drive Strategy for Ignition-Relevant Implosions Using Low LPI Hohlraums with Improved Symmetry Control.

Campaigns	CCR	Hohlraum Diameter (mm)	Pulse Length (ns)	CR	Energy (MJ)
Bigfoot	3.2	5.75	~ 6	~ 20	~1.2
HDC	3.2	5.75	~ 8	~ 30	~1.2
Two-shock	4.25	5.75	~8	~15	~1.0
IFH	3	6.72	~10 – 12.5	~30	~1.6
Be	4.2	6.72	~5.1-8.4	~20-24	~ 1.0
*Wetted foam	3.2	5.75	~6	Variable	~1.0

**Originally planned to use the HDC platform, but may use the two-shock platform depending on target fabrication.*

3.2 Laser Direct Drive

3.2.1 Phases of the Laser Direct Drive IECs

The major deliverables for the five-year IECs are motivated by analysis of OMEGA experimental data and two-dimensional (2D) and three-dimensional (3D) simulations that suggest inadequate laser power balance is the leading cause of performance degradation for fuel adiabats (α) greater than about 3.5 as depicted in Figure 3-4. Similar analysis suggests that the performance of low-adiabat implosions ($\alpha < 3$) is further degraded by shorter wavelength perturbations arising from the target quality at shot time (e.g., target surface particulates and shell imperfections during fabrication) and laser imprint. The combination of long and short wavelength perturbations leads to the break-up of the compressed shell during deceleration and the mix of ablator material into the hot spot. Understanding this behavior is the principal motivation for the IECs.

The 2020 goal is to: 1) demonstrate an inferred hot spot pressure of 100 gigabars and, if unable to do so, understand why, 2) understand LPI mitigation and control at the ignition length scale, and 3) demonstrate the efficacy of physics scaling arguments (such as hydrodynamic-equivalence) for multi-megajoule fusion yield. During each phase, focused physics experiments will be performed to complement the IECs with the goal of understanding and providing data to develop and validate predictive models (see Section 4.2). The combination of integrated and focused experiments, coupled with predictive models, will form the basis for evaluating progress toward the 2020 goal.

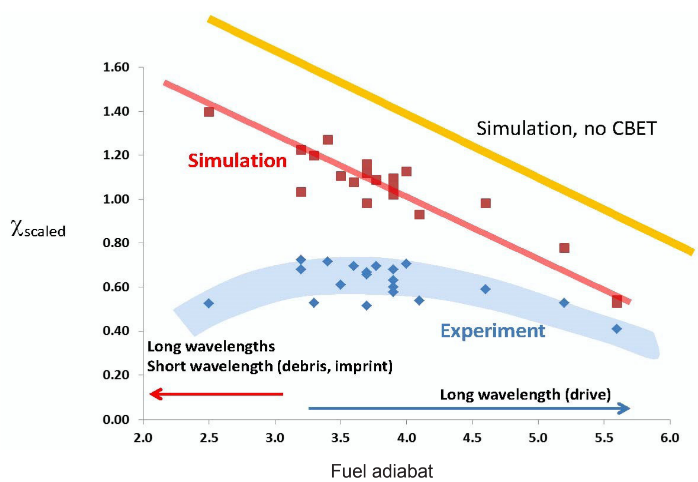


Figure 3-4. Depiction of the Generalized Lawson Parameter scaled to 1.8 MJ calculated for a series of recent OMEGA implosions (the measured performance is shown by the blue diamonds) as a function of the fuel adiabat with (the red boxes) and without CBET (the yellow trend line).

3.2.1.1 Phase 1: Develop Capabilities for High Performance Implosions on OMEGA

The major focus of Phase 1 is to improve the laser, target, and diagnostic capabilities at OMEGA with the goal of conducting hydrodynamic-equivalent implosions in Phase 4. Phase 1 will address the following concerns:

- Improve low-mode drive uniformity and implosion symmetry for high convergence ratios;
- Establish predictive control of the fuel adiabat;
- Mitigate and control laser imprint; and
- Mitigate and control ablator surface and bulk features created during fabrication (e.g., capsule mounting, tubes for fuel filling, target insertion and alignment).

Some imprint control experiments will be done on the NIF, where beam smoothing is limited.

Currently, laser power balance at OMEGA is insufficient for convergence ratios > 17, where low- and mid-mode drive nonuniformities lead to shell breakup near peak burn. Phase 1 will include an extended power balance IEC to ensure that the drive uniformity and implosion symmetry are sufficient for a high convergence ratio implosion of ~ 22-25. In addition, Phase 1 OMEGA experiments will perform with different ablators, target alignment, and drive pulses designed to change the predicted growth rates.

The five-year IECs for LDD will be executed in four phases, with the first three running concurrently.

- *Phase 1. Develop the capabilities for high performance implosions on OMEGA.*
- *Phase 2. Develop and test strategies to mitigate and control LPI.*
- *Phase 3. Advance the modeling and test the limits of 1D physics and 3D predictions.*
- *Phase 4. Test the integrated target performance.*

3.2.1.2 Phase 2: Develop and Test Strategies to Mitigate and Control Laser-Plasma Instabilities

The major focus of Phase 2 is to develop and validate LPI modeling, and identify and test LPI mitigation schemes on OMEGA and the NIF. The primary laser-plasma instability issues are:

- cross-beam energy transfer (CBET),
- two-plasmon decay (TPD), and
- stimulated Raman scattering (SRS).

Phase 2 will test three zooming schemes on OMEGA. In the first, the laser spot profile under fills the target diameter at the start of the pulse, which mitigates CBET at the expense of drive uniformity early in the implosion. The second scheme is to fabricate a dedicated set of "zooming" phase plates such that the inner part of the phase plate generates a larger spot size to match the target diameter at time zero and the outer part generates a smaller spot to match the converged shell size later in the pulse. The third scheme, bandwidth as a mitigation option for high-performance DT-layered implosions, can be tested on the NIF since each set of 48 quads can, in principle, propagate a different wavelength.

NIF experiments will determine if SRS makes significant contributions, since SRS is energetically insignificant at the OMEGA scale. A TPD/SRS mitigation campaign will be developed, with experiments on the NIF and OMEGA. This evaluation requires target fabrication development and the modification of NIF optical diagnostics.

3.2.1.3 Phase 3: Advance Modeling and Test the Limits of 1D Physics and 3D Predictions

The objectives of Phase 3 are to:

- Develop a comprehensive understanding of low convergence ratio (< 17) direct-drive implosions, which are less susceptible to hydrodynamic instabilities, and

- ✧ Test the validity of 1D physics models and the hydrodynamic response with 3D models.

Implosions with a convergence ratio < 17 provide a limiting case of target performance to test the understanding of LDD ICF physics. The strategy is to perform high-adiabat ($\alpha > 7$), low- convergence (~ 10) cryogenic DT implosions and compare them to 1D simulations. The fuel adiabat will be varied to observe when the implosions deviate from 1D behavior. The dependence on laser power balance and target offset will be explored.

Characterized perturbations will be applied to the capsule and the results will be compared with 1D and 3D predictions. Some of these experiments may be done on the NIF as well as on OMEGA.

3.2.1.4 Phase 4: Test of Integrated Target Performance

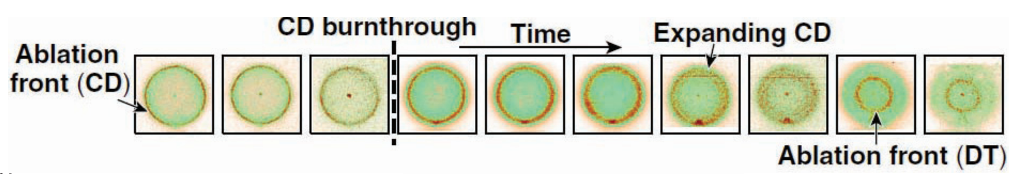
The focus of Phase 4 will be to test the integrated target performance based on the capabilities and knowledge developed during the other three phases. The ultimate goal is to demonstrate LDD implosions with hot-spot pressures of 100 Gbars. This will be accomplished through two integrated experimental campaigns. The intent is to demonstrate near hydrodynamic-equivalent hot-spot pressures consistent with predictions and to understand the "robustness" to initial conditions and engineering features, or to understand why such robustness is not possible.

The goal of the first campaign is to achieve an inferred hot-spot pressure of 80 Gbars. This is the maximum pressure that current predictions suggest is possible without CBET mitigation. New capability requirements developed and tested in Phase 1 will be phased with the experimental schedule as the required laser and target capabilities are attained. No major platform changes are required for the 80 Gbar campaign (see Figure 3-5 depicting a canonical DT implosion on OMEGA).

A new cryogenic target platform is likely required to meet the capsule smoothness requirements of the second campaign, where the goal is to demonstrate a near-ignition, hydrodynamic-equivalent hot-spot pressure of 100 Gbars. This platform would use a fill tube rather than permeation to fill the direct drive capsule with DT fuel. It is expected that CBET mitigation will be required to achieve the 100 Gbars hot-spot pressure.

3.2.2 Detailed 2016 Activities

The major IEC activities in 2016 are summarized below. Many of these IECs will continue beyond 2016. The IECs planned for 2016 for LDD are listed in Table 3-3 at the end of this section.



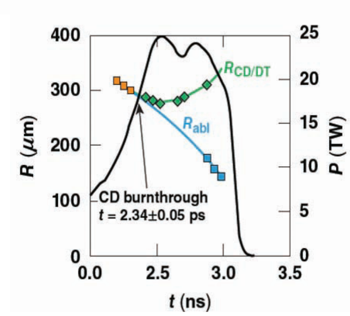


Figure 3-5. A fast x-ray framing camera is used to image the ablation surface during a cryogenic DT implosion (top). Implosion velocity is inferred from the blue points at the end of the laser pulse (the laser pulse is shown by the black trace in the bottom figure). The motion of the CD-DT interface is shown by the green points.

Power Balance

The goal of this campaign in FY 2016-2018 is to test the sensitivity of layered DT implosion performance to deterministic changes in the power balance of the OMEGA laser. Current power balance is a factor of two to three times worse than required for the hydrodynamic-equivalent performance campaigns based on 3D simulations. The campaign will verify the role that power balance plays in the final symmetry of the shell and hot spot during peak burn. Primary diagnostics include in-flight and near stagnation imaging of the shell and stagnation imaging of the fuel hot spot.

FY 2016 goal: Identify and correct 1ω laser energy losses and energy measurement accuracy gaps that could affect the final ultraviolet energy delivered to target and update the Auto Balance algorithms used to determine the optimum 1ω energy balance.

Shock Timing

The goal of this campaign is to verify the prediction of laser coupling and adiabat control in the fuel shell using the cryogenic cone-in-shell platform. In particular, establish a predictive capability for the formation of the main drive shock. Once the platform is established for the main drive shock, these experiments will be conducted routinely as part of the performance and 1D campaigns to verify the pulse shape performance against prediction prior to integrated layered DT implosions. The need to execute these experiments with layered fuel will be assessed. The primary diagnostics include the Velocity Interferometer System for Any Reflector (VISAR) and streaked optical pyrometry.

FY 2016 goal: Verify that target alignment can be maintained at shot time and conduct a series of experiments with increasing main drive intensity.

Ablator

The initial goal of this ambient implosion campaign (non-cryogenic) is to establish ablator options to address LPI control by tailoring the coronal plasma. These experiments will transition to the cryogenic platform once fill-tube capability is established. The initial experiments in this campaign were performed in FY 2015. Tests using the polar direct drive (PDD) implosion platform on the NIF are possible.

FY 2016 goal: Measure the hot electron production and mitigation when applying techniques to reduce CBET in ambient gas-filled implosions.

Zooming

The goal of this campaign is to verify CBET mitigation strategies with implosions on OMEGA. Initial layered DT implosions in FY 2015 showed that reducing light over the capsule horizon by reducing the laser spot size relative to the target diameter reduced CBET as predicted. This occurred, however, at the expense of laser drive uniformity early in the laser pulse. Zooming options that potentially do not impact early time drive nonuniformity include advanced phase plate designs (a prototype has already been fabricated) and dedicated optics that produce a wavelength-dependent spot profile.

FY 2016 goal: A series of imprint efficiency measurements will be taken to quantify the degree to which imprint increases when using a sub-aperture part of an OMEGA beam.

Wavelength Control

The goal of this campaign on the NIF is to establish that the proper use of different laser wavelengths on target can be used to mitigate CBET. The NIF is uniquely capable of producing significant quad-dependent wavelength variations. Changing the wavelength of opposing beams changes the spatial location and, consequently, the level of stimulated Brillouin scattering (SBS) losses. These experiments will be based on the PDD implosion platform.

LLE is scoping options and costs for adding additional laser drivers to study wavelength control using the OMEGA laser toward the end of the decade. (CBET mitigation is necessary for the second hydrodynamic-equivalent performance IEC.)

FY 2016 goal: Experimentally establish the baseline hydrodynamic performance (no wavelength differences) for implosions using the PDD platform on the NIF, where the beams are repointed so that the current NIF wavelength capabilities can be tested with two different wavelengths above and below the equator.

1D Physics

The goal of this campaign is to test the physics models in the hydrodynamic design codes using implosions that are hydrodynamically stable (e.g., fuel adiabats > 7 and convergence ratios of 10) and in which the coupling energetics is well characterized. With a robust 1D platform, parameter scans (adiabat, velocity, convergence) will be performed and the data will be compared with prediction to identify where in parameter space the models need to be improved.

FY 2016 goal: Use four cryogenic DT implosion shot days in FY 2016 to perform an adiabat scan from $\alpha \sim 7$ to $\alpha \sim 3$ using a two-shock, single picket pulse shape. Perform an intensity scan (at least two main drive intensities) at each adiabat while keeping the shock timing fixed.

3D Hydrodynamics

The goal of this campaign is to deliberately add 3D perturbations to the cryogenic DT capsule and/or to the laser drive to compare the measured performance of the shell with 2D and 3D predictions. Examples of the deliberate perturbations include the addition of a dummy stalk, low-mode cryogenic DT and capsule distortions, and drive non-uniformities (by varying the laser energy).

FY 2016 goal: Establish 3D direct-drive modeling and predictive capabilities with the HYDRA code (Lawrence Livermore radiation hydrodynamics code) at LLNL and the new 3D ASTER code at LLE; no campaign-specific experiments are planned in FY 2016.

Table 3-3. Summary of Laser Direct Drive Integrated Experimental Campaign Activities.

Campaign	Facility	Goals	Platform
Power Balance	OMEGA	Improve low mode drive nonuniformity, beam pointing and target alignment stability	Implosions
Shock Timing	OMEGA	Establish predictive adiabat control	Cone-in-shell
Ablator	OMEGA	Demonstrate LPI control using ablator materials to tailor coronal conditions	Implosions
Zooming	OMEGA	Test the concept and performance limits for CBET mitigation	Implosions
Bandwidth Control	NIF, possibly OMEGA	Test the use of wavelength variations to control the SBS process leading to CBET	Implosions
1D Physics	OMEGA	Test the limits of current models, facility capabilities and LPI understanding	Implosions
3D Hydrodynamics	OMEGA, possibly NIF	Test the predictive capability of the 3D hydrocodes against deliberate low mode engineered and drive perturbations	Implosions

✧ **Key**

1D - One-dimensional

3D - Three-dimensional

CBET - Cross-beam energy transfer

NIF - National Ignition Facility

LPI - Laser-plasma instabilities

3.3 Magnetic Direct Drive

3.3.1 Phases of the Magnetic Direct Drive IECs

The major deliverables for the five-year IECs are motivated by calculations of Z performance over a range of achievable peak currents. Figure 3-6 depicts expected performance. Determining the scaling as a function of current of performance and comparing that to calculations is the principal motivation for the IECs.

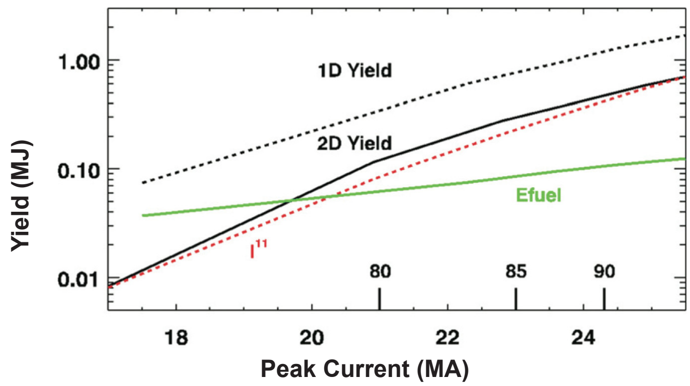


Figure 3-6. Projected performance as a function of peak Z current. The 80, 85, and 90 markers represent the Z Marx charge voltage.

The 2020 goal is to: 1) demonstrate 100 kJ DT equivalent yield and, if unable to do so, understand why, and 2) demonstrate the efficacy of physics scaling arguments (i.e., with current) for multi-megajoule fusion yield. During each phase, focused physics experiments will be performed to complement the IECs with the goal of understanding and providing data to develop and validate predictive models (see Section 5.3). The combination of integrated and focused experiments, coupled with predictive models, will form the basis for evaluating progress toward the 2020 goal.

The five-year IECs for MDD will be executed in two phases somewhat concurrently but with distinct emphases.

- *Phase 1. Complete initial capability to conduct MagLIF experiments at 22 megaamperes (MA) on Z using a seed magnetic field of 30 Tesla (i.e., 30 T) and laser preheating capabilities with energy of 6 kJ.*
- *Phase 2. Optimize ICF target performance and demonstrate neutron yield scaling over the available conditions, with a goal of achieving 100 kJ DT equivalent. In addition, demonstrate magnetization (BR) in excess of 0.5 megagauss-centimeters (MG-cm) and a pressure-time product of 5 Gbar-ns in MagLIF targets.*

3.3.1.1 Phase 1 (FY 2016-FY 2018)

The primary focus of Phase 1 is to demonstrate the physics scaling and increase the neutron yield by enhancing existing capabilities. These enhancements include:

- Deliver more laser preheat energy (from 4.5 kJ to > 6 kJ) to the fuel and co-inject a second laser beam to increase the pulse shaping capability;
- Integrate distributed phase plates in the Z-Beamlet laser to control spot size, pulse shape, and penetration depth for laser energies up to 6 kJ
- Improve the load hardware to increase the current delivered to a target from the present 17-18 MA to 22-24 MA;
- Increase the magnetic field coils in baseline MagLIF target designs from 17-20 Tesla to 30 Tesla;
- Implement methods to reduce the mix of liner material with the fuel and ensure higher compressibility (e.g., electrically-insulated coatings on the liner surface; low density, thick liners); and
- Test new or hybrid target concepts (e.g., MagLIF targets with alternative preheating mechanisms).

A second major Phase 1 focus is conducting the first Z tests with trace amounts (0.1%) of tritium in the deuterium fuel. Even at small percentages, tritium can enhance the scientific understanding and productivity on Z through the use of tritium-related diagnostics developed by the LID and LDD approaches. Processes for handling tritium on a pulsed power facility must also be developed and experience gained in order to credibly define the costs for and operation of an ignition-class facility. The tritium tests are essential to quantify the effectiveness of the containment and the distribution and pathways for tritium migration in Z. In 2017, the initial tests will be extended to 1% tritium in a contained geometry and 0.1% tritium in an uncontained geometry. Without significant new investment, tritium fills to 3%, but no larger, may be possible.

3.3.1.2 Phase 2 (FY 2018 – FY 2020)

For FY 2018-FY 2020, the IECs for MDD will primarily focus on developing optimized targets to demonstrate the scaling of neutron yield to validate the extrapolations to ignition and high yield. Once the key capabilities (e.g., increased laser energy, magnetic field strength, and peak current) have been demonstrated during Phase 1, a number of Phase 2 experiments will explore the different combinations of these variables and diagnose the results. Current levels of 22-24 MA in Phase 2 may be possible by using a combination of higher charge voltages, lower inductance, and more optimal load hardware. At 24 MA, 2D LASNEX calculations predict that an optimized target design with 30 Tesla and > 6 kJ of preheat will produce > 100 kJ DT yield. The validity of these predictions would be the main deliverable of the IECs on Z. Figure 3-7 summarizes the typical measurements made on a MagLIF integrated experiment.

The MDD activities in Phase 2 will include:

- Integrate tritium-containing targets (see discussion in Phase 1);
- Modify the final optics assembly on Z to allow simultaneous laser heating of MagLIF targets and side-on radiography (presently only one or the other can be done); and
- Improve laser preheating to deliver up to 10 kJ by increasing the optics for the second, co-injected beamline to 40-cm diameter (the same as the first beamline).

Depending on the Phase 1 tests, it might be possible to achieve up to 50% tritium fills by 2020 in a contained geometry while using only up to 3% fills

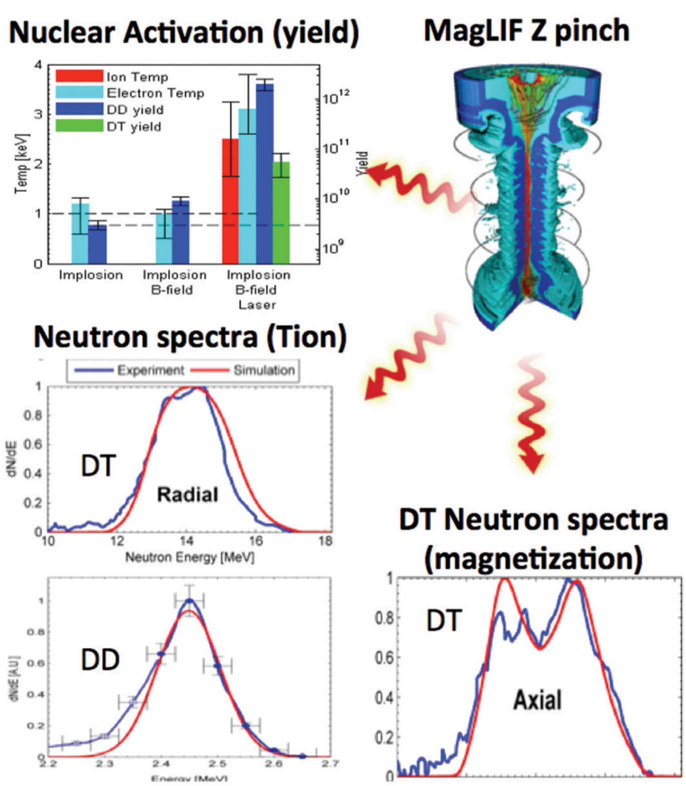


Figure 3-7. Integrated MagLIF experiments produce a wealth of data needed to assess the overall target performance and scaling.

in an uncontained geometry; 50% tritium fills might subsequently be possible in even uncontained geometries. System upgrades for > 3% tritium fills on Z would be expected to include:

- Improve the purging and ventilating of the Z vacuum section;
- Improve the refurbishment tent (where Z hardware is processed after each shot);
- Implement a heating, ventilating, and air conditioning capability for the Z building;
- Improve the neutron shielding (2 x 10^{15} DT neutrons as the present estimated limit);
- Develop a hardware set devoted specifically to tritium experiments; and
- Implement a tritium filling station as well as a tritium capture system.

Sufficient glass and front-end optics may be available from the original Beamlet project to deliver up to 10 kJ. Increasing the laser energy to 10 kJ will require additional experiments to develop the phase plates, laser pulse shapes, and gas fill pressures for the higher energy. The additional preheat energy will increase the likelihood of achieving 100 kJ DT-equivalent yields.

A second Phase 2 objective is to demonstrate some fundamental precepts of magneto-inertial fusion; this objective will require continued improvement of Z's stagnation and burn diagnostics. Concepts such as MagLIF rely on strong magnetic fields to reduce the traditional pressure, density, and ρR requirements for fusion. For sufficiently high magnetization, typically expressed by the parameter BR > 0.5 MG-cm, ignition would be possible even in relatively low-density plasmas. When this condition is satisfied, the charged alpha particles produced by the DT reactions are confined to helical orbits with radii less than the cylindrical plasma radius R. Since the pressure for fusion scales as the product of the density and temperature, reducing the fuel density and ρR by about 100 (e.g., see Figure 3-8) means the pressure can likewise be reduced by a factor of 100. The key metrics for MagLIF experiments on Z are the demonstration of BR > 0.5 MG-cm and a pressure-time product of 5 Gbar-ns.

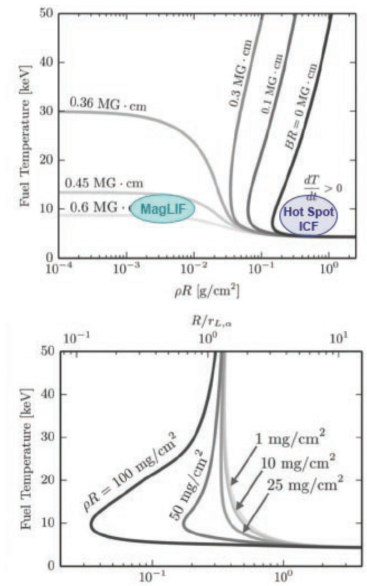
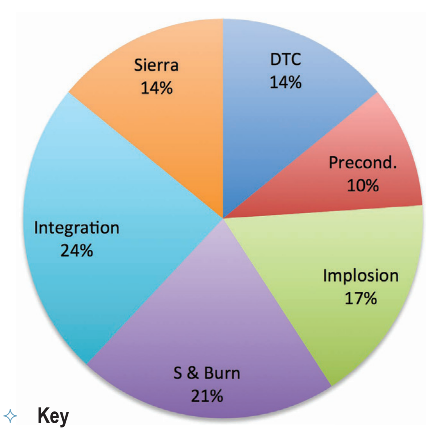


Figure 3-8. Ignition space (dT/dt > 0) plots for magneto-inertial fusion. The MagLIF concept seeks to demonstrate fusion at roughly 100x lower density and pressure than traditional ICF through large magnetic fields (BR > 0.5 MG-cm), which replace ρR as the key metric.

3.3.2 Detailed FY 2016 Activities

The chart in Figure 3-9 illustrates the distribution of ICF shots on Z during 2016. (The Z schedule is defined by calendar year instead of fiscal year.) In keeping with the relative immaturity of the MDD approach, most Z experiments are geared toward focused physics experiments, as defined by the Priority Research Directions (see Section 4.3). Once PRD experiments for MDD studies on OMEGA EP, the NIF, and Z-Beamlet are included (mainly for Target Preconditioning studies), the overall PRD effort is roughly 85%, with the remaining 10-15% devoted to the IECs and associated scaling studies.



✧ **Key**
DTC - Driver-Target Coupling
Precond. - Target Preconditioning
S & Burn - Stagnation and Burn

Figure 3-9. Distribution of ICF program shots on Z in calendar year 2016. The 64 shots for ICF are split between 47 shots for PRDs and 17 shots for IECs.

Specific IEC activities on Z in FY 2016 for MDD are summarized in Table 3-4 and will include the following:

- Implement new phase plates for Z-Beamlet to improve laser-gas coupling to leverage the understanding gained on OMEGA EP at LLE and on the PECOS chamber at SNL;
- Conduct experiments with plastic-coated liners to determine the effect on the 3D stability of the MagLIF target designs;
- Use cryogenically-cooled gas to provide better laser-gas coupling as well as a thick-ended liner to decrease the possibility of laser-induced mix with the fuel; and
- Explore alternative magnetically-driven target concepts.

Stag MagLIF 16a

This campaign uses understanding gained on OMEGA EP at LLE and the PECOS chamber at SNL to explore improved laser-gas coupling by using new phase plates for Z-Beamlet.

Stag MagLIF 16b

This campaign leverages previous experiments on OMEGA EP at LLE and on the PECOS chamber at SNL. The goal is to achieve improved laser-gas coupling using both new phase plates and new laser pulse shapes for Z-Beamlet.

Stag MagLIF 16c

This campaign builds on multi-year implosion research on Z by integrating plastic-coated liners into MagLIF designs to test improvements to the 3D stability of the liner.

Cryo MagLIF

This campaign will integrate cryogenically-cooled gas MagLIF targets into the Z implosion platforms, enabling a much thinner laser entrance window (and hence better laser-gas coupling). The liner design will also be changed to a thick-ended liner to eliminate the need for "cushion" end caps and thus decrease the possibility of laser-induced mix.

Alternative Concepts

Alternative target concept exploration.

Table 3-4. Summary of Magnetic Direct Drive Integrated Experimental Campaign Activities.

Campaign	Gas Fill Pressure	Gas Fill Density	Laser Phase Plate	Laser Energy	No.	Contributors
Stag MagLIF 16a	60 psi D_2	0.7 mg/cc	0.7 mm	2 kJ	2	SNL, LLE, ARPA-E
Stag MagLIF 16b	60 psi D_2	0.7 mg/cc	0.7 mm (or 1.1 mm)	2 kJ/TBD	4	SNL, LLE, ARPA-E
Stag MagLIF 16c	60 psi D_2	0.7 mg/cc	0.7 mm (or 1.1 mm)	TBD	3	SNL
Cryo MagLIF	15 psi D_2	0.7 mg/cc at 70 K	0.7 mm	TBD	3	SNL
Harding (assorted)	-	-	-	-	5	SNL

SNL and LLE at the University of Rochester received a joint two-year Advanced Research Projects Agency-Energy (ARPA-E) Award for a project to explore improved laser-gas coupling for the MagLIF concept. Experiments are being conducted on laser facilities at both SNL and LLE.

The Priority Research Directions

4

The Priority Research Directions define a common taxonomy for fundamental physics experiments to develop and improve models that are ultimately used to predict the performance of highly integrated experiments.

✧ ✧ ✧

The challenge shared by all ICF approaches is the presence of fundamental gaps in understanding the physics of HED environments, particularly as the energy density increases. These gaps drive the use of approximations and empirical models to simulate the complex implosion performance of what are, in reality, complex targets. Researchers are conducting fundamental experiments to replace these approximations and empirical models with physics-based models by incorporating new experimental data. The intent is to improve the accuracy of predictions of target performance for the Integrated Experimental Campaigns (IECs).

The Priority Research Directions (PRDs) define a common taxonomy for fundamental physics experiments to develop and improve models that are ultimately used to predict the performance of ICF experiments executed under the IECs. There are six PRD categories: (1) Driver-Target Coupling, (2) Target Preconditioning, (3) Implosions, (4) Stagnation and Burn, (5) Intrinsic and Transport Properties, and (6) Modeling, Approximations, and Validation. The first four categories map to successive time steps occurring in an ICF implosion, from the delivery of energy from the "driver" (i.e., the laser or pulsed power system) to the target and its implosion, to "stagnation" (the time of peak radiation production) and burn. The fifth category reflects the quantities and look-up tables for the intrinsic material and radiation transport properties through relevant media that are used by computer models to simulate the specific HED environment.

Fundamental physics experiments conducted for the first five categories account for a majority of the facility time set aside for ICF experiments at the NIF, OMEGA, and Z supporting the PRDs. The sixth category refers to the models, integrated simulation codes, and data-driven validation activities that together comprise the "predictive capabilities" used to simulate the implosions.

The PRDs provide opportunities for scientific collaboration among the laboratories and academia. For example, a National Implosion Stagnation Physics Working Group has recently been formed across the three NNSA national security laboratories, LLE, NRL, and academia to develop new hypotheses and recommend discriminating experiments to address the Stagnation and Burn PRD (see page 49 for more information). The PRDs themselves are the product of collaborations, as the inaugural set of the PRDs were the result of the May 2012 Science of Fusion Ignition on NIF Workshop. In FY 2016, representatives from across the ICF community will gather in Santa Fe, New Mexico to update the current set of PRDs to reflect recent progress and future plans.

The following sections describe the fundamental physics associated with the three ICF approaches to ignition. Table 4-1 offers an overview of the fundamental physics associated with the three approaches. The remaining tables in this section provide a technical breakdown of specific challenges that are being actively addressed by the community. This includes a sample of the diagnostics, platforms, and modeling tools being used to improve our understanding of the fundamental physics.

4.1 Laser Indirect Drive

4.1.1 Driver-Target Coupling

The detailed PRDs are provided in Table 4-2 on page 29.

Laser light is propagated into a hohlraum and subsequently converted to x rays, which are in turn transported to the target. Gas-filled hohlraums, which have been the "workhorse" hohlraums used for LID, are not predictable with present simulation codes and are thought to be a significant source of

Table 4-1. Fundamental Physics Associated with the Three Approaches.

Categories	Laser Indirect Drive	Laser Direct Drive	Magnetic Direct Drive
Driver-Target Coupling	• Laser propagation, LPI, and CBET • Hot electron production and transport • X-ray generation and transport • Hohlraum conditions and hydrodynamics • Electron transport and magnetic fields • Time-dependent x-ray drive symmetry and control	• Laser propagation, LPI, and CBET • Hot electron production and transport • Electron transport and magnetic fields • Time-dependent drive symmetry and control (i.e., polar direct drive and spherical direct drive)	• Convolute physics • Current pulse shaping • Current delivery to small radii • Symmetry of current delivery • Optimal power delivery via hardware design
Target Preconditioning	• Shock propagation and timing • Fuel preheating by electrons • Glint (i.e., laser light reflecting off the hohlraum well at early time and impinging directly on the capsule	• Shock propagation and timing • Fuel preheating by electrons • X-ray generation and transport (preheat of mid-Z ablators)	• Laser fuel preheating (LPI window dissembly) • Fuel precompression • Electrothermal instabilities • Early-time contamination • Cyrogenic fuel layer
Implosion	• X-ray ablation and rocket efficiency • Hydrodynamic instability and mix • Role of initial conditions (e.g., roughness, oxidation) • Effects of fill tube and target support structure • Implosion symmetry and control	• Radiative and electron ablation, rocket efficiency • Hydrodynamic instability and mix • Role of initial conditions (e.g., roughness, debris) • Effects of fill tube and mounts • Implosion symmetry and control	• Flux compression • Magneto-Raleigh-Taylor instabilities • Dynamic mix • 3D fuel assembly • Mass flow loss • Radiation losses • Symmetry
Stagnation and Burn	• Power and energy balance, hot spot formation, and properties • Incomplete stagnation, asymmetries, and 3D flow • Deceleration hydrodynamic instability and mix • Radiative cooling	• Power and energy balance, hot spot formation, and properties • Incomplete stagnation, asymmetries, and 3D flow • Deceleration hydrodynamic instability, and mix • Radiative cooling	• Magnetized stagnation and burn • Charged particle stopping • Deceleration instabilities and mix • Non-Maxwellian particle distributions
Intrinsic and Transport Properties	• EOS in compression and release • LTE and non-LTE opacity • Transport coefficients	• EOS in compression and release • LTE and non-LTE opacity in mid-Z ablators • Transport coefficients	• Anomalous cross-field heat transport • Strength and strain • Conductivities • EOSs • Opacity
Modeling, Approximations, and Validation	Integrated within the other five PRDs		

✧ **Key**
3D -Three-dimensional
CBET - Cross-beam energy transfer
EOS - Equation of state
LPI - Laser-plasma instabilities
LTE - Local thermodynamic equilibrium
Non-LTE - Non-local thermodynamic equilibrium

performance degradation due to time-dependent x-ray drive asymmetry and hot electron preheat. The large time-dependent asymmetry is a consequence of CBET invoked to boost the power of the inner cone of laser beams to overcome the poor propagation of those beams to the hohlraum wall. The dominant energy loss for these hohlraums is SRS on the inner cone at a lower limit of ~15% of the total laser energy delivered to the hohlraum. Hohlraums with little or no gas fill may be used to reduce LPI and hot electron production. Figure 4-1 shows an experimental platform used to diagnose plasma conditions in the hohlraum. More advanced hohlraum geometries and designs may help reduce these deleterious effects further.

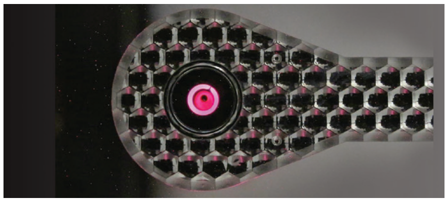


Figure 4-1. The view through the laser entrance hole of the target showing a small dot on the capsule used to track the x-ray emission of the capsule as it ablates.

4.1.2 Target Preconditioning

Shock propagation, fuel preheating caused by hot electrons, and glint (the laser light reflecting off the hohlraum wall at early time and impinging directly on the capsule) all affect the compressibility of the target. Shock propagation before the main pulse is believed to be more predictable compared to the shock(s) launched during the main pulse, where the rate of rise of x-ray drive and hot electron preheat have more impact. Hohlraum designs with very low hot electron production may be used to determine the role of hot electrons on fuel preconditioning and to isolate x-ray drive effects during the rise to peak laser power.

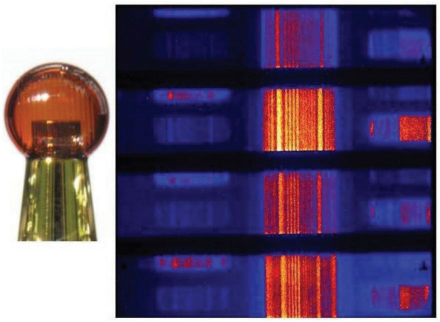


Figure 4-2. A NIF capsule with reentrant cone for measuring instability growth is shown on the left. The capsule has small sinusoidal perturbations etched on the surface. The target is placed in a hohlraum and imploded. On the right is a radiograph of the capsule in flight showing the growth of the perturbations.

4.1.3 Implosion

Implosion hydrodynamics is divided into two areas.

- ✧ The first is 1D phenomena related to the basic physics of capsule implosion, including the pressure generated by x-ray ablation, subsequent shock propagation, material compression, and capsule dynamics.
- ✧ The second is 3D phenomena that degrade the "1D" performance by causing deviation from sphericity, principally by Richtmeyer-Meshkov (shock driven), Rayleigh-Taylor (pressure driven) and Kelvin-Helmholtz (shear driven) instabilities and x-ray drive asymmetry. Figure 4-2 depicts a typical platform for measuring instability growth in HED conditions.

Instability occurs at the ablation front (the outside surface of the capsule, shown in Figure 4-3, at the interface between the inner surface of the ablator and the frozen DT fuel, and on the inside surface of the DT layer. These 3D effects occur during both capsule acceleration and deceleration. Both 1D and 3D phenomena are influenced by material properties (EOS and opacity) and by the x-ray drive spectrum. Surface perturbations lead to ablation-front instability, which may be somewhat mitigated with drive pulse shaping. Capsule mounting and filling features can impact the quality of high-convergence implosions and lead to an asymmetric hot spot in the fuel and also the mixing of the capsule ablator material into the hot spot.

4.1.4 Stagnation and Burn

Ideally, the DT fuel converges to form a central hot spot through hydrodynamic compression by a cooler, denser DT tamping shell that confines

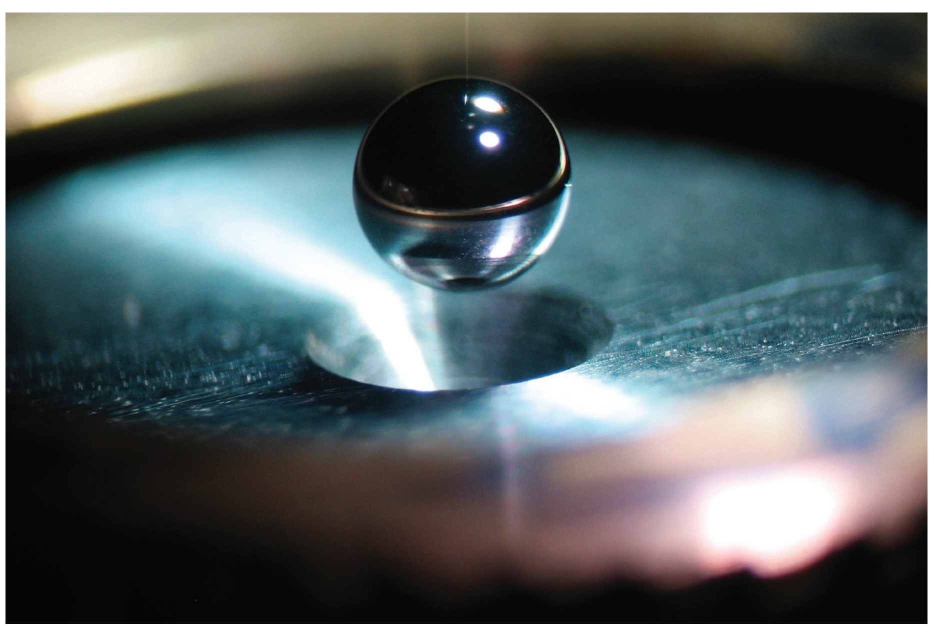


Figure 4-3. A NIF fusion target contains a polished capsule about 2 millimeters in diameter, filled with cryogenic (super-cooled) hydrogen fuel. NIF uses capsules with the outer layer composed of plastic, diamond, or Be.

Table 4-2. Laser Indirect Drive Performance Metrics and Analytic Tools.

Laser Indirect Drive	Metrics	Diagnostics, Platforms, and Modeling
Driver-Target Coupling		
• Laser propagation, LPI, and CBET • Hohlraum conditions and hydrodynamics • Time-dependent x-ray drive and symmetry control	• Absorbed laser energy and x-ray drive • SRS – influences drive symmetry, hot electron production, and energy loss • Drive symmetry – inferred from simulations of surrogate diagnostic targets	**Diagnostics** • Full aperture backscatter diagnostic for SRS, SBS • Gated x-ray images for wall motion and implosion shape • Spectrometers for spectrum, plasma conditions **Platforms** • ViewFactor for drive, laser spot intensity, plasma conditions, wall motion, and Au-bubble imaging **Modeling** • NLTE, thermal transport, LPI, kinetics
Target Preconditioning		
• Shock propagation and timing • Fuel preheating (electrons) • Glint	• Shock velocity and timing – sets minimum fuel adiabat and maximum achievable fuel areal density • Hot electron preheat – increases fuel adiabat constraining areal density	**Diagnostics** • VISAR for shocks, preheat **Platforms** • Keyhole, re-emit (beaming electrons) **Modeling** • EOS, suprathermal electron transport
Implosion		
• X-ray ablation and rocket efficiency • Hydrodynamic instability and mix • Effects of fill tube and tent	• Ablation front instability and growth factors – susceptibility to shell breakup and mix • Implosion symmetry – influences efficiency of energy transfer to hot spot and residual energy	**Diagnostics** • Gated x-ray imagers for shape and hydro growth • X-ray spectrometers for mix **Platforms** • 2DConA tent, fill tube imaging, implosion shape • HGR for instability growth **Modeling** • High resolution hydrodynamics, radiation transport
Stagnation & Burn		
• Power and energy balance, hot spot formation, and properties • Incomplete stagnation, asymmetries, and 3D flow	• Yield, T_{ion}, areal density, burn width, hot spot, and cold fuel size and shape vs. simulated – agreement between observation and best model • Inferred hot spot properties and power balance	**Diagnostics** • Neutron, x-ray spectrometers for T_{ion}, ρR T_e, mix • X-ray, neutron imagers for fuel shape, burn width **Platforms** • Layered DT implosions **Modeling** • Integrated 2D and 3D rad hydro with HYDRA/ARES, synthetic diagnostic signatures
Intrinsic and Transport Properties		
• EOS in compression and release • LTE and non-LTE opacity • Transport coefficients	• Agreement with theory as defined by impacts on major physics drivers (symmetry, compression, hydrodynamic instability, hot spot formation)	**Diagnostics** • VISAR, x-ray backlighting and scattering, spectroscopy **Platforms** • Customized platforms to isolate physics of interest **Modeling** • Assortment of specialized theory-specific codes

✧ **Key**

2D - Two-dimensional
3D - Three-dimensional
CBET - Cross-beam energy transfer
DT - Deuterium-tritium
EOS - Equation of state
HGR - Hydro Growth Rate
LTE - Local thermodynamic equilibrium
NLTE - Non-local thermodynamic equilibrium
SBS - Stimulated Brillouin scattering
SRS - Stimulated Raman scattering
VISAR - Velocity Interferometer System for Any Reflector

the hot spot long enough for self-heating to bootstrap to ignition. Shell symmetry, integrity, and hydrodynamic instability all affect the transfer of energy to and the formation of the hot spot. Figure 4-4 depicts an experiment showing the symmetry of an imploding capsule. Self-heating from alpha particle deposition increases hot spot temperature and pressure, while thermal conduction and radiative loss serve to cool the hot spot. The stagnated fuel down-scattered neutron ratio (a measure of the fuel areal density) is typically ~ 25% below the simulation predictions, while temperatures are somewhat higher than predicted for reasons that are not yet understood. The latter comparison is complicated by the fact that ion temperatures are inferred from the width of the 14-MeV DT neutron spectral peak, which is affected by fuel motion.

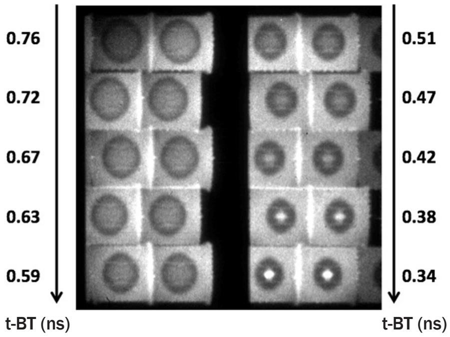


Figure 4-4. A convergent ablator experiment conducted on the NIF. Two x-ray backlit snapshots of the imploding capsule are captured at each time (marked left and right). The time sequence runs top left through bottom right and is marked by time to "bang time" (maximum yield production). The central hot spot can be seen to form late in time (bottom right). Horizontal "scars" resulting from the capsule support membranes can also be seen (top-bottom of each image).

4.1.5 Intrinsic and Transport Properties

Equations of state and opacities of the target components—from partially ionized, weakly coupled regimes to strongly coupled regimes with compressions by factors of ~1,000—are important for modeling capsule implosions. Other important properties include the non-local thermodynamic local thermal equilibrium (non-LTE) physics of the laser-gold interaction; the non-local, potentially-magnetized thermal transport in the hohlraum (which affects plasma temperatures, densities, and x-ray production); the non-local, potentially-magnetized thermal transport from the hot spot into the cold DT fuel (which moderates the hot-spot temperature, mass, and areal density); thermal transport in the warm dense matter regime at the interface between the ablator and the DT fuel (which sets the Atwood number for instability); electron-ion equilibration in the hot spot; and alpha stopping in the hot spot and the surrounding cold fuel.

4.1.6 Modeling, Approximations, and Validation

Integrated modeling incorporates the "best" physics models, validated by experimentation where possible, into HYDRA (the principal simulation code), with the goal of providing a tool to understand target behavior, quantify gaps to reaching ignition, and illuminate potential paths to close those gaps. Large 3D simulations of the implosion, together with data from focused physics experiments, are instrumental in explaining the capsule performance. For low-gas-filled hohlraums where LPI is small, effort is focused on improving non-LTE modeling of gold (and the transition between LTE and non-LTE) as well as non-local thermal transport modeling augmented by validation data. For gas-filled hohlraums, self-consistent, in-line models of LPI and CBET must be added. These additions are being pursued at a reduced rate with the change in the program emphasis to low-density gas hohlraums.

4.2 Laser Direct Drive

4.2.1 Driver-Target Coupling

Direct coupling of laser light to a capsule has a unique set of challenges centered principally on the control of beam-to-beam interactions (also known as CBET), thermal transport, and LPI. CBET can reduce laser coupling, which decreases the implosion hydrodynamic efficiency, the ablation pressure and, consequently the stagnation hot-spot pressure. Thermal transport affects hydrodynamic profiles that govern laser absorption and CBET. The LPI for laser direct drive are similar to those for laser indirect drive. Multiple overlapping beams lead to additional deleterious effects such as TPD instabilities, the threshold and scaling for which have been observed experimentally in relevant configurations.

The detailed PRDs are provided in Table 4-3 on page 34.

4.2.2 Target Preconditioning

As the capsule begins to implode, the shocks in direct drive targets must be accurately timed to ensure the correct fuel adiabat at the end of acceleration.

The cone-in-shell platform used to measure shock coalescence in liquid deuterium with few picosecond accuracy is shown in Figure 4-5 along with an example of the data from the primary diagnostic. Fuel preheating caused by hot electrons can impact the adiabat by changing the properties of the compressed fuel during acceleration. Estimates based on OMEGA experiments suggest that fuel preheating may account for a degradation in compression relative to predictions by up to 10%. To mitigate CBET, a number of novel laser irradiation techniques are being explored. These include laser spot sizes that are smaller than the target, zooming beam sizing, and detuning the laser wavelength. Efforts are underway to assess the impact of these approaches on target preheat, imprint, and low-mode drive nonuniformity. Work is also underway to validate the modeling of hot electron suppression by using mid-Z layers in the ablator.

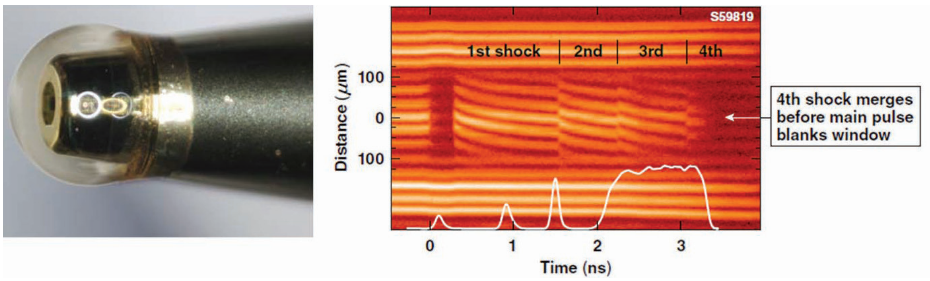


Figure 4-5. A cone-in-shell target (left) is used to measure the shock strength and coalescence for drive pulses used on OMEGA. The VISAR diagnostic looks through the cone at the inner surface of the shell. The VISAR data on the right shows discontinuities in the fringe patterns as the shocks catch up with the leading shock.

4.2.3 Implosion

Direct drive implosions are sensitive to surface debris that can initiate instability growth on short-length scales and illumination power imbalance that can initiate longer-wavelength mode growth. Short-length-scale instabilities limit the adiabat (i.e., compressibility) of the implosion and weaken the shell integrity when coupled with Rayleigh-Taylor and Richtmeyer-Meshkov instabilities, resulting in the mix of cold fuel and ablator material into the hot spot. Long-wavelength modes lead to an asymmetric hot spot, increased hot-spot volume, and reduced inferred pressure. Capsules may be coated with this layer to reduce laser imprint.

4.2.4 Stagnation and Burn

Deuterium-tritium fuel assembly in LDD is determined by hot spot and stagnating shell symmetry, hot-spot internal energy, and RKE, and anomalous thermal conduction (from magnetic fields). Figure 4-6 depicts the x-ray image of an imploding direct drive target on OMEGA. A larger hot-spot volume than simulated is mainly associated with early stagnation caused by ablation-front hydrodynamic instabilities and fuel-hot-spot mix. Target performance is limited by core asymmetry that leads to larger hot-spot volumes and reduced pressures. Asymmetry in the shell areal densities amplifies RKE, reducing the hot-spot internal energy and pressure. Experiments to address these

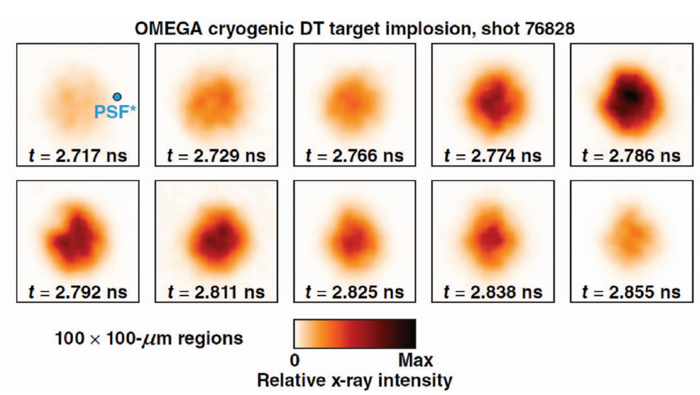


Figure 4-6. A sequential series of x-ray core images of an imploding direct drive cryogenic target on OMEGA. The bang time is 2.78 nanoseconds.

Table 4-3. Laser Indirect Drive Performance Metrics and Analytic Tools.

Laser Indirect Drive	Metrics	Diagnostics, Platforms, and Modeling
Driver-Target Coupling		
• Laser propagation, LPI, and CBET • Electron transport and magnetic fields • Time-dependent drive symmetry and control	• CBET – coupling losses reduce the ablation pressure requiring mitigation strategies • Mass ablation rate – determines ablator hydro efficiency and validates coupling models	**Diagnostics** • Optical Thomson scattering • Full aperture backscatter diagnostic for SRS, SBS **Platforms** • Mid-Z doped & layered ablators • Ablation surface and shell trajectories **Modeling** • Improved CBET modeling based on first principle calculations (LLE and LLNL)
Target Preconditioning		
• Shock propagation and timing • Fuel preheating (electrons) • X-ray generation and transport (preheat for mid-Z ablators)	• Shock velocity and timing – sets minimum fuel adiabat and maximum possible fuel ρR • Imprint–high spatial frequency seeds for RT instability growth at the ablation surface	**Diagnostics** • 660nm VISAR laser plus optics • Streaked Optical Pyrometry • X-ray streak cameras **Platforms** • Through-shell cone-in-shell radiography **Modeling** • Improved 2ωp modeling using LPSE developed at LLE)
Implosion		
• Radiative and electron ablation, rocket efficiency • Effects of fill tube and mounts • Implosion symmetry and control	• Implosion symmetry – few percent-level laser power imbalance influences shell uniformity at stagnation and residual kinetic energy • Ablation front instability – susceptibility to shell breakup and hot-spot mix	**Diagnostics** • Aspheric Crystal Imaging (soft x-ray backlighting) • Streaked x-ray continuum **Platforms** • Layered DT targets using fill-tubes • In-flight shell radiography w/soft x-ray backlighting **Modeling** • First-principles EOS modeling for relevant ablators and hydrogen
Stagnation & Burn		
• Power and energy balance, hot spot formation, and properties • Incomplete stagnation, asymmetries, and 3D flow	• 1.9 MJ hydrodynamics-equivalent yield – expectation of SDD performance at 1.9 MJ • Hot-spot shape and radius – stagnation symmetry, convergence, and hot-spot pressure • RKE–energy that does not heat the fuel	**Diagnostics** • 3D nTOF • Neutron Temporal Diagnostic • Streaked x-ray continuum (T_e) **Platforms** • 1D - lower convergence designs • Spherical strong shock **Modeling** • Direct-drive 3D modeling (Aster)
Intrinsic and Transport Properties		
• EOSs in compression and release • LTE and non-LTE opacity in mid-Z ablators • Transport coefficients	• Fuel/shell compressibility, conductivity, and opacity – first principles modeling • Hot spot mass – ablation from the inner ice surface • High Z opacity – assess use for imprint mitigation	**Diagnostics** • Framing and streak cameras, VISAR, spectroscopy **Platforms** • Side-on radiography, impedance matching, implosions, transmission **Modeling** • First-principles EOS for relevant ablators and hydrogen

✧ **Key**

2D - Two-dimensional
3D - Three-dimensional
CBET - Cross-beam energy transfer
DT - Deuterium-tritium
EOS - Equation of state
LLE - Laboratory for Laser Energetics (University of Rochester)
LLNL - Lawrence Livermore National Laboratory
LPSE - Laser plasma simulation environment
LTE - Local thermodynamic equilibrium
NLTE - Non-local thermodynamic equilibrium
nTOF - Neutron time of flight
RKE - Residual kinetic energy
SBS - Stimulated Brillouin scattering
SRS - Stimulated Raman scattering
VISAR - Velocity Interferometer System for Any Reflector

limitations are planned. The effect of smaller beams that introduce larger, low-mode asymmetry will be assessed. An assessment will be performed on the NIF to study CBET mitigation of low-mode asymmetry by wavelength separation.

4.2.5 Intrinsic and Transport Properties

Cryogenic direct drive implosions reach a strongly coupled and degenerate plasma regime where the static, transport, and optical properties of warm dense plasmas are not well known. Currently, quantum molecular dynamics and Path-Integral Monte-Carlo methods are used to establish first-principles EOSs, thermal conductivity, and first-principles opacity values of DT over a wide range of densities and temperatures relevant for low-adiabat implosions. These properties determine the shell compressibility, the optical properties of compressed material, the final shell densities, and stagnation pressures as well as the amount of radiation heating from the plasma corona—all of which influence the implosion performance.

4.2.6 Modeling, Approximations, and Validation

LDD modeling uses the 2D DRACO code and the 3D HYDRA code to understand the physics of the implosion. Important physics in these simulations are laser deposition via CBET and nonlinear heat conduction as well as the effect of preheat from TPD and possible SRS on the adiabat. The DRACO physics models have been verified with the 1D LILAC code for spherical drive. LLE and LLNL are implementing noise-free ray trace and CBET into the HYDRA code. Validation of the DRACO code for a PDD geometry with OMEGA and NIF experiments is ongoing. Hybrid LPI and hydrodynamic simulations have been developed with limited success.

There are ongoing challenges to this LDD PRD. Code validation with NIF experiments is challenging because of the significant non-uniformity in laser illumination due to inadequate single-beam smoothing and LID distributed phase plates not optimized for LDD. Multiple large-scale simulations in 2D with CBET and imprint and in 3D OMEGA cryogenic simulations exceed LLE's present computing resources. In addition, the integration of LPI models in radiation-hydrodynamics codes leads to unrealistically long run times. Therefore, a comprehensive LPI simulation toolkit, i.e., Laser Plasma Simulation Environment (LPSE), is under development to provide guidance on the development of more computationally friendly LPI models for the hydrocodes. NRL is also working with LPSE to develop LPI modeling options for their FAST code.

Plans are being made to address these concerns by continuing 3D code development on HYDRA, wavelength detuning experiments on the NIF to study CBET mitigation based on DRACO predictions, 3D simulations of all OMEGA cryogenic and NIF PDD experiments, smoothing by multi-frequency modulation, and NIF TPD experiments to understand TPD sources and transport to improve DRACO models.

4.3 Magnetic Direct Drive

4.3.1 Driver-Target Coupling

Pulsed power machines store and discharge electrical energy, compressing that energy in space and time. In the final stages of the compression, complex arrangements of conductors combine into a single anode-cathode gap just before reaching the target. The electrical current pulse amplitude and timing can be varied to tailor the drive conditions at the target ("pulse shaping"). The pulse shaping is critical to avoid undesirable current loss and/or voltage asymmetry. Within the target, plasma instabilities can affect the delivery

The detailed PRDs are provided in Table 4-4 on page 37.

of the current to small radii, placing effective limits on the peak magnetic pressure that is achievable.

4.3.2 Target Preconditioning

The target implosion increases the plasma density and raises the plasma temperature to the conditions needed for fusion. For some MDD designs (such as MagLIF), strong magnetic fields are used to inhibit thermal conduction losses. In addition, a laser is used to preheat the fuel prior to the implosion. This enables more stable liners to compress the fuel. Figure 4-7 depicts the emission due to laser heating on a MagLIF development experiment. Methods for heating the fuel can introduce contamination, leading to increased radiation loss during the implosion. Prior to becoming a plasma, the flow of current in the metal liner volume can create instabilities, which can then seed the magneto-Rayleigh-Taylor instability during the implosion stage.

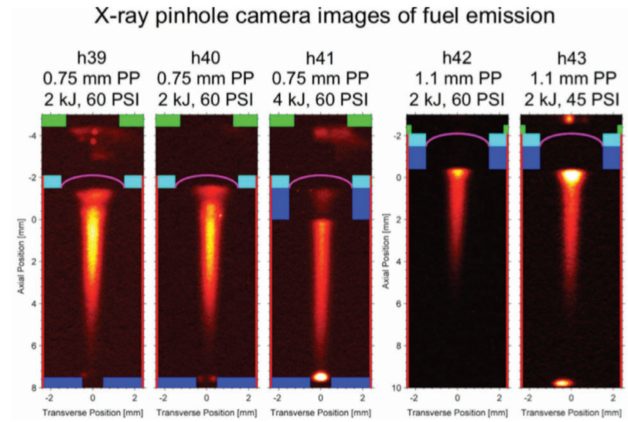


Figure 4-7. Emission from fuel due to heating of the preheat laser.

4.3.3 Implosion

Magnetic pressure can be used to compress liner targets containing fusion fuel, with the drive and acceleration increasing during the implosion as the magnetic field strength increases. The dominant instability during the implosion phase is the magneto-Rayleigh-Taylor instability. This can create significant asymmetry and 3D structure. Figure 4-8 shows evidence of early time instabilities. The natural implosion geometry is cylindrical, hence the fuel within can be lost out of the ends during long implosion times. The long implosion time of magnetized and preheated implosions means that radiation losses have significantly more time to occur. The compression of magnetic flux by the plasma liner is good, but not perfect, and the models have not been validated at these plasma densities.

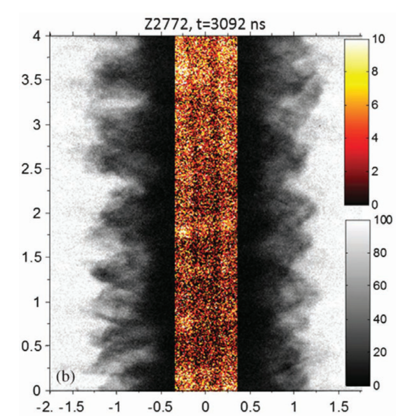


Figure 4-8. Radiograph of a MagLIF implosion.

4.3.4 Stagnation and Burn

As the fuel plasma pressure increases, it eventually becomes comparable to the magnetic drive pressure, and the liner and fuel begin to decelerate, leading in turn to a variety of potential deceleration instabilities (Rayleigh-Taylor, Kelvin-Helmholtz, etc.). The compressed magnetic flux in the fuel is typically chosen so that the charged particles produced in fusion reactions (tritons, alpha particles) are strongly magnetized with Larmor radii less than or equal to the plasma radius. This can enhance the trapping of charged particles in the fuel, depending on the plasma and field geometry. In many z-pinch plasmas, there is ample evidence that a large fraction of the high-energy ions never fully thermalize, leading to non-Maxwellian particle velocity distributions at the highest particle velocities that are largely responsible for the fusion reactions. Self-emission from a MagLIF target at stagnation is depicted in Figure 4-9.

Table 4-4. Magnetic Direct Drive Performance Metrics and Analytic Tools.

Magnetic Direct Drive	Metrics	Diagnostics, Platforms, and Modeling
Driver-Target Coupling		
• Power delivery and hardware optimization • Current pulse shaping • Current delivery to small radii • Symmetry of current delivery	• Optimizing implosion time – increased implosion time can reduce losses (lower dI/dt) • Pulse shaping – Possible to increase implosion stability by maintaining material strength	**Diagnostics** • Load current B-dot probes **Platforms** • Mykonos: Pulsed power facility that can be used for scaled power-flow experiments under conditions similar to those on future facilities **Modeling** • Explore hybrid particle-in-cell models for plasma losses in power-flow regions
Target Preconditioning		
• Laser fuel heating (LPI, window disassembly) • Fuel pre-compression • Electro-thermal instabilities • Early-time contamination • Cryogenic fuel layer	• LPI – limit the coupling of laser energy into the fuel before compression in MagLIF, which increases the velocity & convergence requirements	**Diagnostics** • Spherical crystal x-ray imaging (backlighting or self-emission) • X-ray spectroscopy (temperature, mix) **Platforms** • Scaled-down MagLIF experiments on OMEGA (ARPA-E funded) **Modeling** • Improved conductivity, EOS for new liner materials
Implosion		
• Flux compression • Acceleration and deceleration instabilities • Dynamic mix • Mass flow loss • Radiation losses • Symmetry	• MRT instability – The dominant instability during the acceleration stage • Flux compression – achieving high magnetization at stagnation requires compressing initial magnetic field (affected by "Nernst" losses)	**Diagnostics** • Optical Faraday rotation fibers (magnetic flux compression) **Platforms** • Dedicated acceleration and deceleration instability studies on Z **Modeling** • Validate and improve magneto-hydrodynamic models in multiple codes, including higher-order approximations (e.g., Nernst)
Stagnation & Burn		
• Magnetized stagnation and burn • Charged particle stopping • Deceleration instabilities and mix	• BR product – Representative of how magnetized electrons and fusion products are at stagnation; replaces areal density (rho-R) as the key criteria in magnetized targets • Fuel shape – Deformed cylindrical assembly will lose benefit of pZ and increase losses	**Diagnostics** • Neutron spectrometers for T_{ion}, BR, yield, particle distributions • X-ray, neutron imagers for fuel shape visualization **Platforms** • Tritium capability development experiments on Z **Modeling** • Explore hybrid particle-in-cell models for current losses in high-convergence implosions, as well as non-Maxwellian particle distributions
Intrinsic and Transport Properties		
• Anomalous cross-field heat transport • Strength, strain • Conductivities • EOSs • Opacity	• Liner and shell compressibility, conductivity, and opacity (affects inertial confinement) • Fuel temperature and magnetization during implosion (as indicator of heat transport)	**Diagnostics** • Spherical crystal x-ray imaging (liner dynamics) • Optical emission/spectroscopy (fuel temperature) **Platforms** • Implosion experiments to measure T_e, B versus time **Modeling** • First principles DTF calculations of Li EOS

✧ **Key**

ARPA-E - Advanced Research Projects Agency-Energy
B - Magnetic field
BR - Magnetization
DFT - Density Functional Theory
EOS - Equation of state
LPI - Laser plasma instabilities
MRT - Magneto Raleigh-Taylor instability
Li - Lithium
LTE - Non-local thermodynamic equilibrium
MJ - Megajoule
nTOF - Neutron time of flight

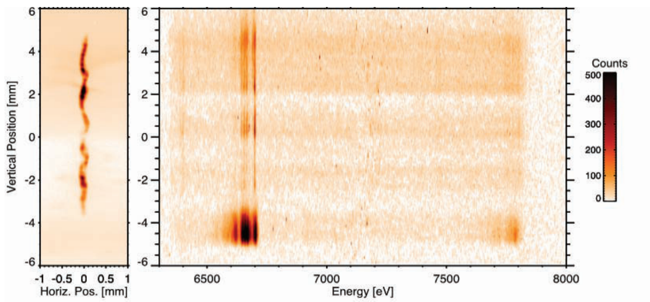


Figure 4-9. Self-emission x-ray image of the high-temperature plasma from MagLIF at stagnation (left), x-ray emission spectra from hot liner material mixed into the fusion fuel (right).

4.3.5 Intrinsic and Transport Properties

Accurate electrical conductivity models are important for modeling the preconditioning and implosion phases of the metal and plasma liners. In some cases, the current pulse shape can be tuned to leave a portion of the liner volume in a near-solid state for a significant fraction of the implosion, making strength, strain, and EOSs important. Models for the inhibition of electron transport in magnetized system are known to have anomalies that require corrections (Braginskii models). These have not been validated in most of the plasma density and temperature ranges of interest. Material opacities play a limited role in the success of typical magnetically-driven target approaches but are extremely important for the analysis of data from these plasmas.

4.3.6 Modeling, Approximations, and Validation

Magnetically-driven target implosions are modeled similarly to laser-driven systems, provided that the electromagnetic forces are added to the simulation tools. A key problem is that liner implosions typically involve plasmas that are both too low in density for fluid-based approximations to be truly valid, and too high in density to allow the motion of particles to be directly modeled by particle-in-cell methods. Fluid-based approximations can often miss the key physics, and extending particle-in-cell calculations to higher densities requires the use of hybrid approximations that need to be better understood. Laser-heating and LPI are extremely difficult to model. Two-dimensional simulations are particularly prone to error, since the liner dynamics are demonstrably 3D in nature when magnetized.

National Diagnostics Plan

5

Recognizing the need for enhanced coordination to develop advanced ICF diagnostics, the ICF/HED community formed the National Diagnostics Working Group of technical experts in 2009.

The scope of diagnostics considered in the NDP is characterized as:

- *Transformational: Major national efforts with the potential to transform experimental capability for the most critical science needs across the complex.*
- *Broad: Significant national efforts that will enable new or more precise measurements across the complex.*
- *Local: Important efforts involving the implementation of known technology for a particular facility need.*

Recognizing the need for enhanced coordination to develop advanced ICF diagnostics, the ICF/HED community formed the National Diagnostics Working Group (NDWG) of technical experts in 2009. Seventeen institutions participate in the NDWG, including LLNL, LANL, SNL, LLE, GA, NRL, and MIT, and other organizations such as Princeton Plasma Physics Laboratory and industry. International involvement from the Atomic Weapons Establishment of the United Kingdom and Commissariat à l'Energie Atomique et aux énergies alternatives (CEA) of France also contributes to the depth and breadth of the NDWG. The group has focused on the development and fielding of diagnostics to support national missions for NNSA's ICF/HED experimental facilities, in particular, NIF, Z, and OMEGA, and OMEGA EP.

The NDWG developed a National Diagnostics Plan (NDP) through multiple workshops and focused technical meetings. The NDP is updated annually and regularly reviewed by an external panel of subject matter experts.

The NDWG identified eight transformational diagnostics in the NDP, as shown in Table 5-1. These will provide unprecedented information on the implosion physics in fusion-relevant regimes, determine the plasma conditions created by both laser and pulsed power drivers, and enable dynamic measurements over a range of relevant conditions on the properties of materials utilized in nuclear weapons. The data provided by these diagnostics will validate and improve the physics contained within the multi-dimensional simulation codes, and will uncover and quantify important phenomena that lie beyond our present understanding.

5.1 Transformational Diagnostics

During 2015, the NDWG found a number of innovations for more optimal technological solutions that improved performance, decreased cost, and accelerated deployment. Examples of these innovations are:

- Use of a simpler recording technology for neutron imaging would accelerate the scheduled implementation of polar imaging of unscattered neutrons by more than 2 years with a decrease in cost of $5 million.
- The potential of GaAs diodes for 15-40 keV x-ray detection on hCMOS cameras would accelerate the schedule for high-energy, single line of sight (SLOS) detection by 1 year.
- Use of an existing NIF Preamplifier Module at LLE for the front end of the NIF Optical Thomson Scattering (OTS) laser would accelerate the schedule by 6 months.

Table 5-1. Summary of the First Eight Transformational Diagnostics Formulated by the NDWG.

Acronym	Name	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22
CMOS/SLOS	Hybrid CMOS/SLOS	2-frame; Z & NIF	4-frame; Z/NIF/Ω	SLOS+KB	8-frame	40 keV diodes; SLOS+Wolter	16-frame		
OTS	Optical Thomson Scattering		Xtal (LLE); Laser	Emission NIF	Ω, NIF				
NIS	3D Neutron/Gamma Imaging			Polar		Polar n/g(time)		Eq NIS/GRI	3D n & γ
GCD	Gamma Spectroscopy		Bkg	20ps; ~1 meter	start GEMS				
MRS-t	Time Resolved Neutron Spectrometer				CD-readout	NIF			
HIRES	High Resolution X-ray Spectrometer		EP (static)	EP (t), NIF (static)	NIF (t); Ω (t)	NIF Exo-chamber			
Wolter	Hard X-ray Imaging			Z (static)		NIF (SLOS); Z (SLOS), NIF (50 keV)			
Diffraction	Time Resolved Diffraction			NIF (GXD)		Z (static)	NIF (SLOS); Z (t)		

✧ Testing the first "single line of sight" on OMEGA during Q1 FY17 would accelerate the schedule by about 6 months.

Technical Readiness Level and Schedule for Transformational Diagnostics

Each of the transformational diagnostics includes multiple phases, realizing both near-term and longer-term implementation of capabilities on the facilities with increasing precision. Table 5-2 shows the estimated Technical Readiness Level (TRL) of the least mature phase. One of the goals of the NDP is to provide the impetus to bring each of these projects to a TRL of 9. Table 5-2 also shows the expected completion date of the entire project. Portions of each project will be deployed much earlier than the date listed.

Hybrid CMOS. A SLOS detector (see Figure 5-1) will provide multi-frame, high-time-resolution measurements of optical or x-ray signals with about one million pixels. For images requiring ~ 10 ps time resolution, the fast signal can be stretched by a "pulse dilation tube" to match the several-nanosecond gate time of this detector. This technology would replace micro-channel plate (MCP) detectors that have been the standard for more than 20 years in this and many other applications. This capability will overcome many MCP limitations by providing high dynamic range, flexible and shorter gate times, the ability to absolutely calibrate the detector system, and the ability to record many time-gated images along a SLOS. This is a general technology that will transform capability for all missions on the large HED science facilities through improved precision and resolution in x-ray imaging and spectroscopy.

Optical Thomson Scattering (OTS). OTS irradiates a small plasma region with a probe laser and uses broadening of the scatted light to measure electron and ion temperature and density and collective behavior. OTS has been implemented for many years on Nova, Trident, the Jupiter Laser Facility, and OMEGA, and

Table 5-2. Minimum Technical Readiness Level and Expected Completion Date of Each Transformational Diagnostic.

Diagnostic	TRL Today	Estimated Completion
CMOS/SLOS	4	2020
OTS	6	2018
NIS	6	2020
GCD	3	2019
MRS-t	3	2019
HIRES	6	2019
Wolter	5	2019
Diffraction	4	2020

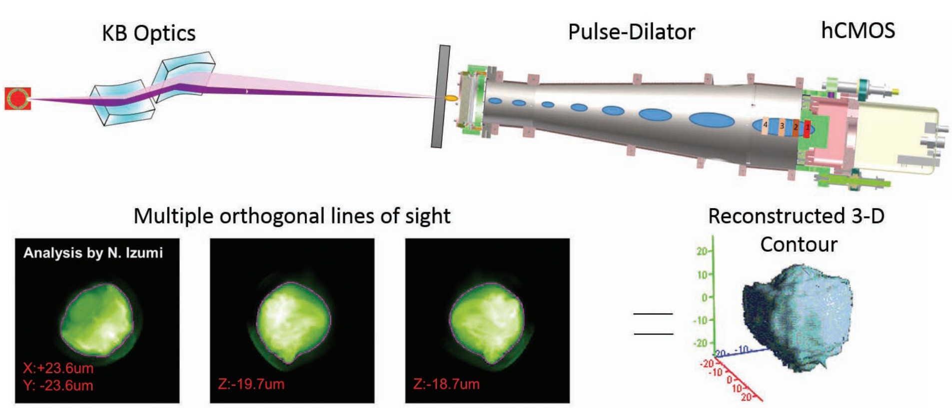


Figure 5-1. (Top) Layout of the SLOS imager. Projections of what the SLOS would image are provided at bottom left. A reconstruction using those three projections is given at bottom right. Three orthogonal LOS can theoretically provide some 3D information. Modeling Analysis: N. Izumi.

it has demonstrated its fundamental feasibility for HED applications. The transformational concept adopted by the NDWG is to use a deep ultraviolet laser to allow scattering in a spectral region where the background from the NIF or OMEGA laser beams and their harmonics are not overwhelming. A major challenge is developing a drive laser compatible with the NIF architecture. Potential applications are characterizing hohlraum plasmas and evolution for LID, laser entrance window interaction and gas heating for MDD, underdense plasma characterization for LDD, and electron transport and plasma characterization for intrinsic and transport properties studies.

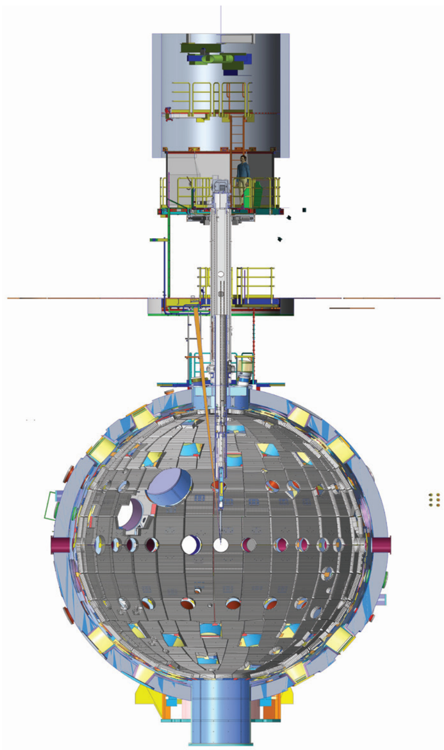


Figure 5-2. Drawing showing the near polar NIS on the NIS target chamber. The near polar NIS will provide a nearly orthogonal view to the present equatorial NIS. It is being designed to be compatible with the present polar x-ray imager.

3D Neutron/Gamma Imaging (NIS). The NIS (see Figure 5-2) will provide three views to capture neutron images in order to measure the fuel distribution at stagnation, the time at which neutrons are generated, and the time when 3D structure is affecting nuclear performance. This diagnostic allows tomographic reconstruction of the hot spot and cold fuel distributions for comparisons to 3D simulations. A measure of this fuel structure is also important in interpreting the data from the suite of nuclear data that is collected on each experiment. Measurement of the fuel distribution allows consideration of the effect on the other diagnostics as well as isolation and measurement of other processes that degrade nuclear performance.

Gamma Spectroscopy (GCD). The GCD provides improved time resolution in reaction history and ablator areal density measurements for comparison to predicted signatures of alpha heating and mix seen in recent simulations. This necessitates diagnostic capability improvements in both sensitivity and temporal response relative to the existing Gamma Reaction History diagnostic (GRH-6m) located 6 meters from the target chamber center. With improved time resolution, the GCD could potentially study hot spot formation and burn propagation, ablator and hot spot mixing, capsule areal density evolution, and ion-electron equilibration, as well as nuclear astrophysics phenomena.

Time Resolved Neutron Spectrometer (MRS-t). Magnetic Recoil Spectrometry with time dependence (MRS-t) enables time-resolved measurements of the fusion neutron spectrum. This diagnostic provides a time history of the trajectory of areal density and ion burn temperature (ρR-Ti) that is important for diagnosing the performance of capsules at or near ignition conditions. The MRS-t diagnostic is developed by MIT (see *University Partnerships: Massachusetts Institute of Technology* on page 43 for a description of that partnership).

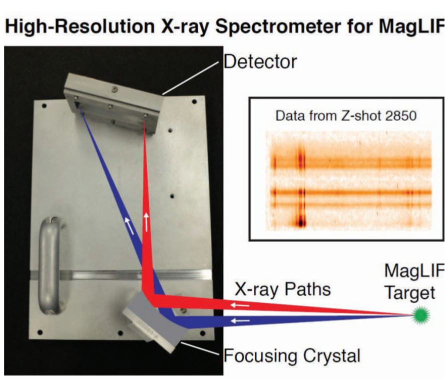


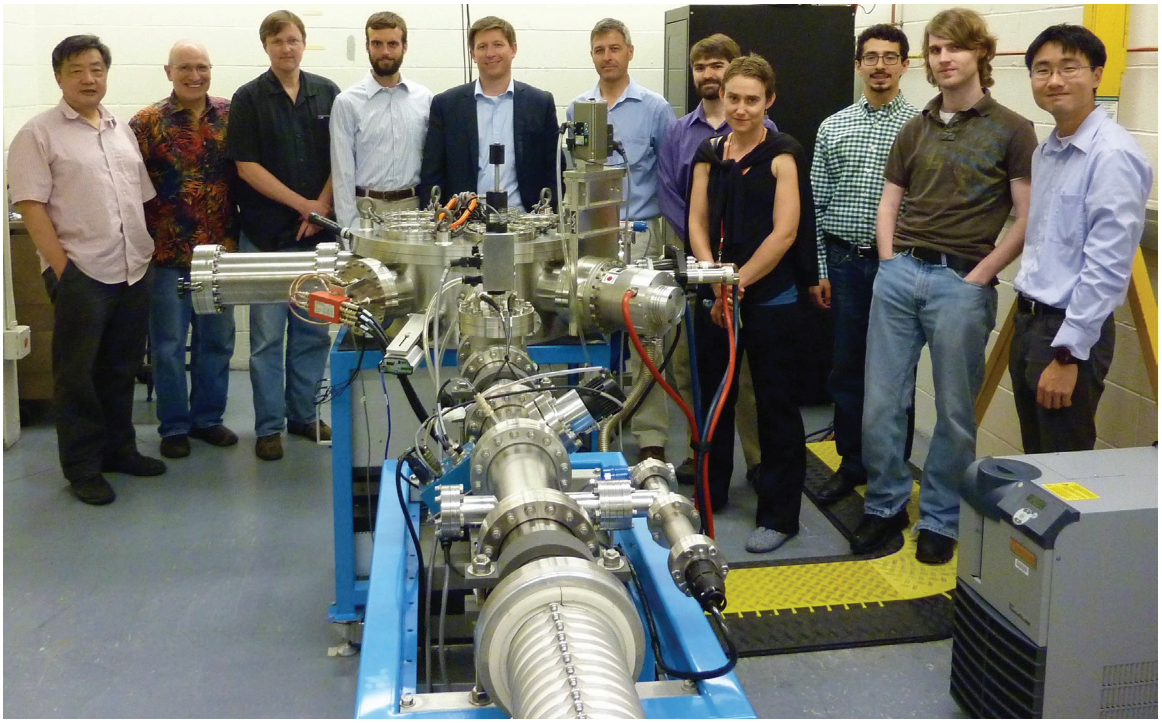
Figure 5-3. High-Resolution X-ray Spectrometer for MagLIF.

High Resolution X-ray Spectrometer (HiRes). High resolution spectroscopy (with a resolving power ~ 5000) on HED facilities will enable new experiments in many areas of HED physics and warm dense matter (see Figure 5-3). For instance, experiments on OMEGA have employed x-ray absorption fine structure to measure the temperature of cold, compressed iron. This technique will be extended to Z and the NIF. Presently, the density of the hot spot of NIF implosions is inferred indirectly from measurements of the neutron yield, ion temperature, neutron time of flight (nToF), and the size and duration of implosions. Better constraints on the models used in predictive simulations will require direct density and temperature measurements through line-ratio, Doppler-broadened, and Stark-broadened measurements of dopants in the hot spot enabled by high-resolution spectrometers.

Hard X-ray Imaging (Wolter). Advanced x-ray optics developed mainly for space applications, such as the Wolter microscope, will improve signal to noise ratios, improve spatial resolution, and provide energy resolution for x-ray imaging at photon energies > 15 keV. This diagnostic is needed for detailed

Massachusetts Institute of Technology

University Partnerships



Massachusetts Institute of Technology (MIT). *NNSA's Dr. Keith LeChien and LLNL's Dr. John Edwards met with students and scientific staff of the MIT HEDP Division of the Plasma Science and Fusion Center for a day of lively scientific discussions and tours of the MIT HEDP experimental facilities. During the day, six MIT PhD students presented and discussed salient aspects of their HEDP research, which involved the design and building of instrumentation and the subsequent data collection and analysis from their experiments fielded at NIF, OMEGA, and Z. One of the most recent accomplishments, oft discussed during the day, was the implementation at the NIF of the D^3He charged-particle radiographic "backligher." This platform, which consists of an implosion of a D^3He filled capsule, and is the work of PhD students Hong Sio, Brandon Lahmann, Graeme Sutfcliffe, and Neel Kabadi, under the guidance of MIT scientists Chikang Li and Fredrick Seguin, and LLNL scientists Ryan Rygg and Sebastien LePape, is able to simultaneously generate intense ~ 75 ps pulses of monoenergetic particles of 14.7 MeV and 3.0 MeV protons, and 3.6 MeV alphas and 1.0 MeV tritons. This set of particles are then used to radiograph the evolution and detailed structure of fields and plasma flows of HEDP experiments. Very recently, this platform was utilized in two NIF experiments to reveal exquisite details of collisionless shocks and the properties, hitherto unobservable, of warm-dense matter. Shown above is the HED accelerator facility where students and staff tested and developed, prior to implementation at the NIF, the radiographic and high-speed detectors used in these experiments. (From left to right: Chikang Li, Richard Petrasso, Johan Frenje, Alex Zylstra, Keith LeChien, John Edwards, Hans Rinderknecht, Maria Gatu-Johnson, David Orozco, Hong Sio. Alex Zylstra and Hans Rinderknecht, PhD students in the HEDP Division, are now Reines and Lawrence postdoctoral Fellows at LANL and LLNL, respectively. Both obtained critical data for their theses from NIF and OMEGA experiments.)*

measurements of the source performance in z-pinch and laser-produced x-ray sources for radiation effects sciences. Wolter optics can replace pinholes in the SLOS imaging system to provide high-fidelity, time-resolved gated images. The improved imaging capability will enhance experiments on material strength and complex hydrodynamics using high resolution radiography, ICF implosion dynamics and stagnation characterization, and non-thermal x-ray production.

Time Resolved Diffraction. Time-gated x-ray diffraction will provide time-dependent measurements of phase change in materials at high pressure. Near-term improvements would adapt existing framing cameras to the TARDIS configuration to provide time-resolved capability (see Figure 5-4). For the longer term, adapting the SLOS detector for this application would enable multiple diffraction images over time, allowing the observation of the evolution of crystal structure. Likewise, x-ray diffraction techniques will be developed for Z starting with single-frame measurements and evolving to multi-frame measurements in later years. Time resolved diffraction will enable measurement of the kinetics of phase transitions at high pressures and multiple phase transformations on a single shot (for example, melt-refreeze).

The phasing of the Transformational Diagnostics implementation plan is summarized below. That plan is dependent on resource allocation, which is subject to change.

5.2 Broad Diagnostics

The “Broad Diagnostic” category includes eight important scientific and engineering efforts that are common to all three facilities but are not characterized as transformational. These broad efforts are reviewed by the community at many focused workshops.

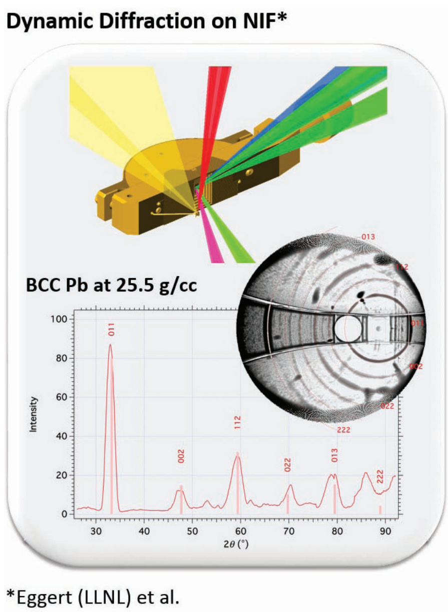


Figure 5-4. The TARDIS captures diffraction images of a material under dynamic compression. This data is used to determine the phase of the material.

Neutron Time of Flight

Neutron time of flight detectors have been used for decades at NNSA ICF/HED facilities. As the complexity of stagnation physics becomes more apparent, the NDWG has recognized the importance of increasing both the number and the accuracy of the nTOF detectors at the NIF, Z, and OMEGA. A joint project named ‘Precision nToF’ is being pursued to improve the measurement accuracy and to understand the information encoded in the neutron emission spectrum from the burn, including the deviations from a Gaussian shape.

In parallel with an improved understanding of the requirements of nToF, more of the detectors are being built at the three facilities. This activity is in a variety of phases. A new north-pole nToF is being commissioned on the NIF in Q3 FY16. An antipodal nTOF and two new shielded lines of sight are being built on OMEGA between now and 2019. A gated nToF will be installed on Z in FY 2016 and a far field nToF is planned for Z in later years. These diagnostics will aid in understanding the physics of “stagnation” by quantifying the kinetic energy in the core of the implosion.

Hard X-ray Detection

As the temperature of the plasmas in these facilities increases, the x-ray emission energy increases. In addition, as the areal density of the plasmas increases, harder x-rays are needed to probe the plasmas. Unfortunately, the sensitivity of x-ray detectors decreases as the x-ray energy increases because the x-ray absorption of all materials drops. The problem of sensitivity is exacerbated for sub-nanosecond detectors, which traditionally need to be thin in order to preserve high time resolution. A broad activity is in place to test advanced detectors. SNL is developing 3D diodes. National Security Technologies, LLC and LLNL are jointly developing structured photo-cathode detectors. Each of these approaches increases the path length of photon-interaction within the detector material without significantly sacrificing temporal resolution. The goal is accurate data on x-ray emission from higher temperature plasmas for ICF, on radiography of higher density (areal density) objects for ICF and HED, and on diagnosing K-shell emission from x-ray sources for radiation effects science.

Radiation Hardening Against Neutron and Gamma Ray Backgrounds

As the neutron yield increases on all the ICF facilities and the high energy Bremsstrahlung x-ray background increases on Z, there is a negative impact on solid-state, e.g., charge-coupled device (CCD), detectors ranging from a few bright spots to complete failure. LLNL and commercial vendors are producing a CCD-like detector (a CMOS focal plane array) that will work at neutron and gamma background levels two orders of magnitude higher than current

CCDs using a technique called 'dump and read'. In this technique, the short-lived background from neutrons and gammas is continuously recorded by the detector but then dumped just prior to recording the x-ray signal from the afterglow of a phosphor that continues to emit after the background radiation has passed. This type of device will also be available to Z and OMEGA. These detectors will be able to record data at higher yields and will improve operational efficiency by requiring less facility reconfiguration for high yield shots.

Time Dependence of the Stagnation Electron Temperature Through X-ray Spectroscopy

The electron temperature during stagnation can be measured from the emission spectrum of high-energy x-rays that pass through the cold material surrounding the hot stagnating core. X-ray focusing spectrometers fielded close to the source with new SLOS detectors and/or streak cameras can measure this emission spectrum with up to 20-picosecond resolution. A new set of spectrometers and x-ray streak cameras that can operate in the harsh neutron and gamma environment inside the target chambers is being developed for the NIF, OMEGA and Z. The NIF spectrometer and time-resolving detector (x-ray streak camera) should be available in FY 2017 (see Figure 5-5). Time-integrated focusing spectrometers already exist on Z, and plans exist to couple these to SLOS detectors in the next few years. Like the neutron temporal diagnostic (NTD) below, these spectrometers will measure the energy input to and energy loss from the stagnating core based on how quickly the core heats and cools.

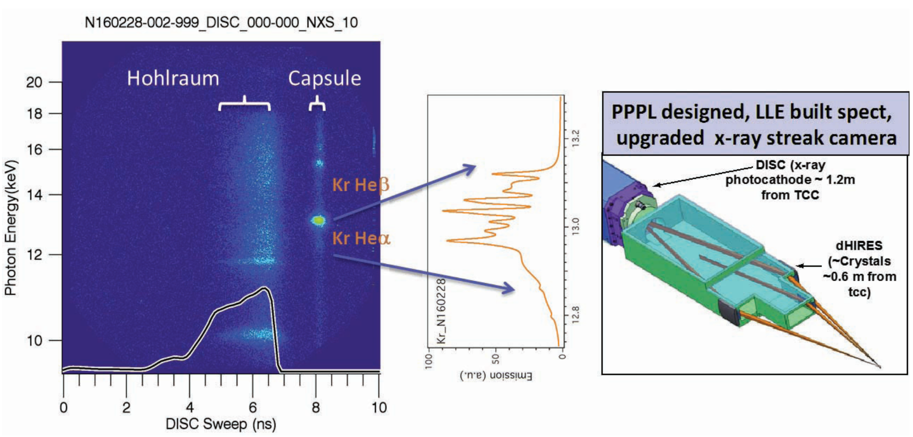


Figure 5-5. X-ray spectroscopy on NIF implosions. A time resolved spectrometer shows that doped implosions on NIF emit weak He like krypton (Kr) lines (left). The calculated fine structure of the Kr Heα line is shown (middle). A high resolution focusing spectrometer (right) will resolve fine features in the two Kr lines shown.

Neutron Temporal Diagnostic

The time history of the neutron emission is measured on OMEGA with the recently upgraded NTD. The diagnostic records the time dependence of the TN burn to an accuracy of 40 ps with a dynamic range of ~ 100. On OMEGA the time of peak burn as measured by NTD shows that burn is being quenched earlier than expected. The importance of this OMEGA measurement has led to the question of whether a similar diagnostic should be built for the NIF. A LANL, LLE, MIT, and LLNL group is assessing the benefit and difficulty of developing a NIF NTD. When successfully fielded, an NTD-like diagnostic will accurately measure the quenching of burn or, in the case of alpha particle heating, the peaking of burn at the threshold of ignition.

Pulsed X-ray Calibration Source

Time dependent x-ray detectors on all three facilities need regular calibration as their response changes on monthly timescales as they are exposed to the harsh environment inside the target chambers of the NIF, Z, and OMEGA. Making an off-line calibration source with sufficient brightness is difficult for some of the facility diagnostics and so facility shots are used for in-situ calibrations. An SNL/LLNL industry working group has designed a source bright enough for off-line calibration. In parallel, an LLNL/CEA collaboration has used an off-line short-pulse ultraviolet laser as an alternate short-pulse calibration capability. The techniques are being compared.

Curved Crystal Imaging

Z and OMEGA both use a focusing x-ray crystal to image with very narrow bandwidth x-ray emission or to image x-ray backlit experiments. Based on these successes, an effort is underway to build a Curved Backlighting Imager (CBI) for the NIF. The very narrow bandwidth will allow the NIF to record the shape of the ablator close to or at the time of peak burn. In the future, these crystal imagers will be combined with SLOS detectors to provide narrow-bandwidth, time-resolved, high-spatial-resolution images. The CBI will measure the effect of time-dependent asymmetry of drive for high convergence implosions.

Magnetic Field Capability on the NIF

Most of the work on MagLIF is performed on the Z facility using the Z-Beamlet laser to preheat the fuel. The laser preheat phase of the MagLIF concept is being studied on OMEGA and will be studied on the NIF, where higher laser energy and better optical diagnostics are available. A magnetic field capability is part of the OMEGA facility mainly for academic users through the National Laser Users' Facility; this capability will be upgraded from 10 Tesla to 30 Tesla. An SNL/LLE/LLNL group is designing a magnetic field capability of up to 70 Tesla for the NIF. This capability will allow studies of preheat uniformity in laser-produced plasma for MagLIF as well as studies of the effect of an applied magnetic field on implosion performance.

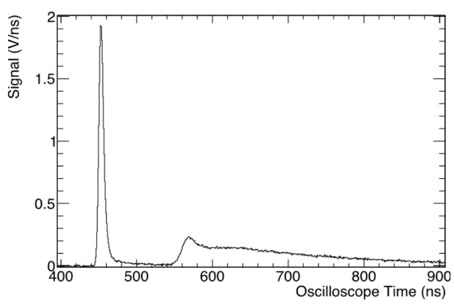


Figure 5-6. The NIF nTOF diagnostic shows for the first time a peak in the T-T neutron spectrum due to decay through the the ground state of ^{5}He (seen at 570 nsec in the figure.)

5.3 Local Diagnostics

The "Local Diagnostic" category covers those new and improved diagnostics principally for one of the three large facilities by using known technologies. These diagnostics are often campaign specific and associated with the education of students. This list of existing local diagnostics is long, in excess of 100 on OMEGA, 60 on the NIF, and 50 on Z. Local diagnostics evolve and are added more quickly than the transformational or broad diagnostics. Some *examples of further work on local diagnostics include the following*.

Optical. This category includes Photon Doppler Velocimetry and the line VISAR to measure the load current on Z, streaked visible spectroscopy to measure the plasma and field strength in the feeds for Z, a sub-aperture backscatter station to measure the back scatter on OMEGA EP, and enhancing the backscatter into the beam diagnostics on the NIF.

X-ray. This category includes the MCP in-chamber pinhole imager on Z, coated x-ray microscopes on the NIF, various in-chamber add on (snouts) for OMEGA and the NIF, a high-spatial-resolution x-ray streak camera for the NIF, and 7-8 keV radiography on Z, laser entrance hole imaging and spectroscopy for Z, and Bremsstrahlung MeV x-ray spectrometer to measure laser plasma coupling on OMEGA EP.

Nuclear. This category includes additional flange neutron activation detectors on the NIF (example neutron signatures depicted in Figure 5-6), higher-sensitivity radiochemistry on the NIF. (LANL and GA duplicated a high-sensitivity detector for off-line measurements of radiochemical samples from the NIF. The original detector system remains at LANL and is used to measure slightly longer-lived isotopes.)

Scientific Peer Review and the 2020 ICF Program Goal

6

6.1 Overview

The principal 2020 goal of the ICF Program is to determine the efficacy of NIF for achieving ignition and the credible physics scaling to multi-megajoule fusion yields for each of the major ICF approaches. *A key challenge is to clearly demonstrate that ICF has achieved this goal and that in each of the intervening years we are, in fact, on a path to achieve it.*

The general 2020 goal specifically maps to each of the approaches in the following manner (reproduced from the IEC section):

- LID: The 2020 goal is to: 1) demonstrate the efficacy of the NIF for achieving ignition and, if unable to do so, understand why, and 2) demonstrate the efficacy of physics scaling arguments for multi-megajoule fusion yield.
- LDD: The 2020 goal is to: 1) demonstrate an inferred hot spot pressure of 100 gigabars and, if unable to do so, understand why, 2) understand LPI mitigation and control at the ignition length scale, and 3) demonstrate the efficacy of physics scaling arguments (such as hydrodynamic-equivalence) for multi-megajoule fusion yield.
- MDD: The 2020 goal is to: 1) demonstrate 100 kJ DT equivalent yield and, if unable to do so, understand why, and 2) demonstrate the efficacy of physics scaling arguments (i.e., with current) for multi-megajoule fusion yield.

The principal 2020 goal of the ICF Program is to determine the efficacy of NIF for achieving ignition and the credible physics scaling to multi-megajoule fusion yields for each of the major ICF approaches. A key challenge is to clearly demonstrate that ICF has achieved this goal and that in each of the intervening years we are, in fact, on a path to achieve it.

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A "demonstration" of these goals has been achieved by producing a quantitative assessment of and associated evidence for:

- the state of the assembled fusion plasma at stagnation (see the *National Implosion Stagnation Physics Working Group* sidebar on page 49),
- an assessment of factors that explain measured performance deviations from calculated performance,
- the underlying assumptions for and validity of physics-scaling arguments, and
- the uncertainties associated with the above.

The demonstration must be subjected to scientific-based peer review. Peer review is important since technical arguments advanced by such a demonstration would also be advanced for assertions of physics scaling (i.e., scaling to higher laser or pulsed power system energies). Quantifying uncertainties is also extremely important, as is clearly identifying and bounding the underlying assumptions being made in scaling arguments both for the target physics and the driver technology. Together with programmatic drivers, these assessments provide the framework against which decisions on future investments can be made.

6.2 Measuring Progress Toward the 2020 Goal

Traditionally, progress towards ignition and assertions of physics scaling have been evaluated using the Lawson criteria ($P\tau$), where P is the plasma pressure and τ is the confinement time as a function of temperature T. More recently, a Generalized Lawson Parameter was developed[1], $\chi = (P\tau)/(P\tau)_{ign}$, where $P\tau_{ign} \sim 1/T^2$, as a convenient and informative metric for the proximity to ignition conditions. Another metric[2] is Y dsr[2] where Y is the fusion yield and dsr is the down-scattered neutron ratio defined as $Y_{10\text{-}12MeV}/Y_{13\text{-}15MeV}$.

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[1] R. Betti et al., "Thermonuclear ignition in inertial confinement fusion and comparison with magnetic confinement," Phys. Plasmas 17, 058102 (2010).

[2] B. Spears and J.D. Lindl in "Review of the National Ignition Campaign 2009-2012," Phys. Plasmas, 21, 020501 (2014).

When the DT fuel is magnetized, another important metric is B·r, which is a measure of alpha particle trapping in the hot spot with radius r due to the magnetic field with strength B. Together, these provide useful, approximate cross-platform metrics of implosion quality, however, the performance of any given implosion is not uniquely described by any of these metrics, whether the performance is 1D or highly distorted.

Specific direction for a given ICF approach is guided by complex simulations which each approach will extrapolate to make assertions regarding physics scaling, may that be by driver energy, pressure, or some other parameter. Therefore, a critical evaluation and quantification of uncertainties in the extrapolation is central to this exercise, and to any assessment of the validity of scaling arguments. The evaluation and quantification must go far beyond simple statements based on the above zero-dimensional or low-dimensionality parameters, and it must include detailed uncertainty estimates in:

- the state of the assembled fuel from which scaling is to be done,
- the simulation models or theory that attempt to reproduce the demonstrated performance and are used to extrapolate, and
- the physics models in the simulation tools and the magnitude of the effects of the physics not included.

In particular, models are often calibrated to match certain important experimental inputs that have measurement uncertainty that must be accounted for, such as the implosion velocity. This adds additional challenges regarding assertions of scaling. Further, it is possible that we will reach a point where irreducible aleatory uncertainties associated with process control may dominate our residual prediction uncertainties, again, adding to the challenge of qualifying assertions of physics scaling.

A description of the challenges regarding physics scaling for each approach is detailed below.

6.3 Specific Needs to Support Physics-Scaling Arguments Associated with the 2020 Goal

6.3.1 Laser Indirect Drive

Important products of the PRDs are calibrated physics-based simulation tools that allow interpolation and extrapolation over parameter space of interest, replacing empirical models and experimental scaling (see comparison between calculations and measurements for low- and high-foot in Figure 6-1). Over time, the goal of the PRDs is to improve the fidelity of the physics models in those simulation codes as experiments, theory, and computer power advance.

Driver-Target Coupling

Develop a 2D radiation-hydrodynamics model that can reproduce the observed x-ray drive, spectrum, and symmetry in hohlraums that exhibit low levels of LPI. Record any remaining experimental calibrations, hypotheses, and physics uncertainties. Understand the resulting uncertainty in predictions of these quantities.

Fuel Preconditioning

Understand whether shock velocity and timing measurements are consistent with the observed x-ray drive spectrum particularly during the rise to peak power, taking into account experimental uncertainties. Record discrepancies and develop associated hypotheses.

National Implosion Stagnation Physics (NISP) Working Group

In the context of inertial confinement fusion (ICF), "stagnation" has traditionally been thought of as the state of maximum fuel compression where kinetic energy has been converted into thermal energy and the majority of the fusion reactions take place. The reality is that the 'stagnating' plasma remains dynamic: there are many processes occurring during this critical phase of the implosion history. It is prohibitive to simultaneously measure a given particle's (ion, electron, and fusion product) energy distribution as a function of 3D space and time in an ICF implosion, we instead form a physical understanding of a stagnated plasma through an ensemble of highly integrating diagnostics. The precise "stagnated" state also cannot be easily simulated with complete physics, so we typically rely on models that use physics approximations.

To improve the understanding of the physics of "stagnation," NNSA established the NISP Working Group in summer 2015. The NISP has been working on defining peer-reviewed, distilled physical pictures of the stagnated fuel and ablator/liner for all three ICF approaches that are consistent with existing data and informed by simulations. The goal is to task a national team with peer-reviewing these physical pictures, generate hypotheses for the inconsistencies between the physical pictures and observations, and develop a plan to address these inconsistencies that may require new diagnostics, experiments, and analyses methods.

Implosion

Develop predictive models of hydrodynamic instability on the outside of the capsule as observed in-flight, seeded by engineering features and native capsule surface and/or internal structure for ablators of interest. Develop improved understanding of capsule initial conditions, "seeds." Record any remaining experimental calibrations, hypotheses, and physics uncertainties. Understand the resulting uncertainty in predictions of these quantities.

Develop predictive models of implosion asymmetry as observed in-flight due to radiation drive asymmetry. Record any remaining experimental calibrations, hypotheses and physics uncertainties. Understand the resulting uncertainty in predictions of these quantities.

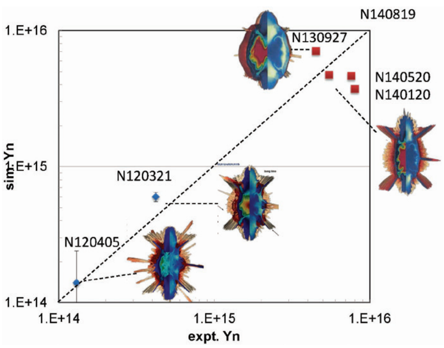

Figure 6-1. 3D simulations of low-foot (lower left) and high-foot (upper right) experiments with comparisons between simulated and measured neutron yields.

Stagnation and Burn

Develop full-sphere 3D implosion models that incorporate improvements in modeling from the other PRDs and best models for hot spot physics. Develop improved analyses of experimental data and reduce error bars. Compare synthetic diagnostic signatures with experimental observations, including an evaluation of uncertainties in both experiment and theory. Record discrepancies, associated hypotheses, and supporting evidence.

Intrinsic Properties

Understand the resolution and detail required to accurately model high Z hohlraum emission in non-local thermodynamic equilibrium in the context of overall hohlraum energetics and spectrum. Develop an improved model for use in radiation hydrocodes. Record best knowledge of uncertainties in models of intrinsic properties, and resulting sensitivity of predictions. Assess the magnitude of the impact of kinetic effects and magnetic fields on target physics.

6.3.2 Laser Direct Drive

Implosion plasma scale lengths on OMEGA are ~4 times shorter than on the NIF for energetically equivalent designs. Nevertheless, OMEGA can be used to study designs that are predicted to reach the same hot-spot pressures as ignition designs for the NIF that would produce multi-megajoule fusion yields. A key objective for the IECs is to demonstrate the scaling of hot-spot pressure over conditions available on OMEGA, and LDD-related LPI concerns on the NIF (see Figure 6-2 for a comparison of calculations as a function of capsule position). A key objective for the PRDs is to determine the credibility of the physics models contained within the simulation tools.

Testing the physics implicit in LDD design tools will be accomplished in part by focused science experiments conducted under the PRDs. The following describes the major five-year goals for the PRDs that are critical for underpinning scaling arguments for LDD.

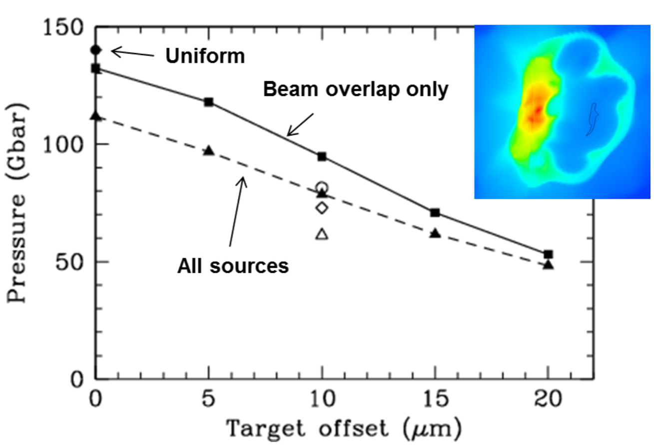

Figure 6-2. Implosion hot-spot pressure calculated as a function of target offset from target chamber center. The upper curve shows the expected performance imposed by the reduced beam overlap. The lower curve includes the reduce beam overlap combined with a laser power imbalance. The open symbols show the impact of increasing each of these contributions by 2x. The image shows a meridional cut through the simulation of the shell areal density at bang time with a 20-micrometer offset.

Driver-Target Coupling
Validate thermal transport models for the multi-dimensional hydrocodes. Establish and test scalable models for LPI (SRS, TPD, SBS). Verify mitigation strategies for CBET at OMEGA and the NIF.

Target Preconditioning
Verify mitigation strategies for hot-electron production and fuel preheating at the OMEGA and NIF scales. Test scalable models for shock formation, propagation, and coalescence.

Implosion
Verify the power balance requirements for symmetric high convergence (CR > 20) implosions on OMEGA. Understand the sources of ablator mixing into the hot-spot.

Stagnation and Burn
Develop measurement techniques to understand fuel compression, confinement, and RKE at peak burn. Use 3D hydro simulations to compare with and guide quantitative measurements.

Intrinsic and Transport Properties
Develop and validate models for fuel and ablator compressibility, conductivity, and opacity.

6.3.3 Magnetic Direct Drive

Present simulation capabilities suggest that the MDD approach on the existing Z pulsed power facility is not capable of achieving multi-megajoule fusion yields. The requirements to achieve such yields will be defined using the best available simulation tools. The challenge of determining the credibility of these tools is described below. A key objective for the IECs is to demonstrate the scaling of neutron yield over conditions available on Z. A key objective for the PRDs is to determine the credibility of the physics models contained within the simulation tools (see Figure 6-3).

Testing the physics implicit in our design tools will be accomplished in part by focused science experiments conducted under the PRDs. The following describes the major five-year goals for the PRDs that are critical for underpinning scaling arguments for MDD.

Driver-Target Coupling
Conduct scaled power-flow experiments under conditions similar to those present on the higher-current facilities predicted today to be necessary to achieve multi-megajoule fusion yields, with the goal of developing predictive models for the coupling of such accelerators to a variety of targets.

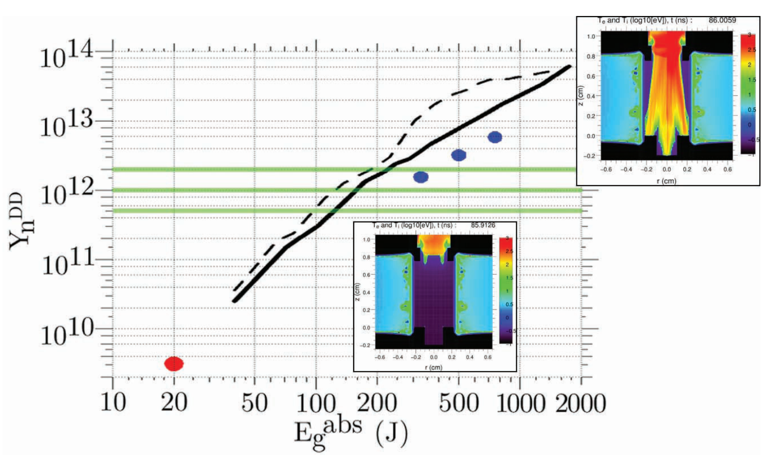

Figure 6-3. HYDRA calculations of integrated MagLIF yields as a function of laser energy coupled to the fusion fuel (assuming no mix). The yield from the initial experiments is shown as horizontal green bars.

Target Preconditioning
Demonstrate 30 kJ, magnetized laser heating of fusion gas cell targets on the NIF, to reduce the need for scaling extrapolations to the conditions needed for multi-megajoule fusion yields.

Implosion
Demonstrate the ability to model acceleration and deceleration instabilities using the same codes used to predict the integrated target performance.

Stagnation & Burn
Develop diagnostics, measurements, and models for the stagnation plasma on Z that will allow us to infer the key variables of interest (ion temperature, magnetization, fuel pressure, P-Tau, fuel contamination, and shape/uniformity).

Intrinsic & Transport Properties
Determine the validity of models for magnetized electron heat transport and magnetic flux compression in regimes relevant to MagLIF.

6.4 Establishing Devil's Advocate Red Team to Continuously Evaluate Progress Toward the 2020 Goal

Fixed resources require a prioritization of the body of work that will be executed. It is critical to ensure that the focus is on the most important aspects that will lead to achieving the 2020 goal. The Devil's Advocate Red Team will be instrumental in vetting the physics-scaling arguments advanced by the LID, LDD, and MDD efforts.

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The phase-space one would like to explore through the IECs and PRDs is quite large for each approach. There are, however, fixed resources which require a prioritization in the body of work that will be executed. As such, it is critical to ensure that the focus be on the most important aspects that will lead to achieving the 2020 goal. Therefore, the arguments put forward to establish the prioritization by the LID, LDD, and MDD teams must be subjected to scientific scrutiny all along the way.

To address this, in FY 2016 the ICF Program Director will convene a team of experienced and respected technical experts known as the Devil's Advocate Red Team (DART). A devil's advocate is assigned the responsibility of finding the weaknesses of an argument or claim (a so-called "devil's opinion" on the matter). In the same way, this team will be charged with finding any weaknesses in the program's technical arguments toward the 2020 goal and of the potential effects of any major facility upgrades or changes in program emphasis. Members of DART will individually report to the Federal Program Director. The ICF Executives will facilitate the work of DART and will assure full cooperation with DART's requests and provide prompt, complete responses to their inquiries. The goal of DART is to:

- ask harder, more penetrating questions than could be asked by any external body,
- assure the soundness of technical cases that underlie statements of achievement of the 2020 goal and for any other major programmatic decisions, and
- assure that the technical case that underlies assertions of physics scaling and estimates of uncertainty withstand scientific scrutiny.

DART will convene regularly, holding a "tribunal" in which the leads of the LID, LDD, and MDD efforts will present their arguments. DART will provide written individual opinions to the ICF Program Director as to their assessment of progress toward the 2020 goal.

ICF/HED Capabilities and the Next 20+ Years of Stockpile Stewardship

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Initial ICF/HED capability improvements for the science-based SSP were described in the first SSMP, which was published in 1996. That SSMP included an extensive technical discussion regarding the rationale for particular ICF/HED capabilities. Not surprisingly, there are a few differences between what was discussed then, and what is discussed regularly today. Regarding ICF/HED capabilities, the following capabilities were listed in the first SSMP:

- the NIF, the Advanced Radiation Source (ARS or X-1), and the Atlas pulsed power capability under the heading "Program Needs for Assessment and Certification,"
- Pegasus, PBFA-Z, high explosive pulsed power (HEPP) capabilities, Atlas, ARS/X-1, Nova, OMEGA, the NIF, Saturn, and BEEF under the heading "Response to Surveillance Issues,"
- Atlas, the NIF, HERMES, HEPP, Z, Saturn, and ARS/X-1 under the figure titled "New Capabilities are Needed for Assessment and Certification," and
- the ARS/X-1 as an "intermediate step" to a new HED pulsed power facility called Jupiter under the figure titled "Secondary Assessment Plan."

Over the last 20 years, some of these capabilities were pursued, and some were to come online "later" in the SSP.

The establishment of the SSP brought about the obvious question of whether the Nation could maintain a safe, secure, and effective nuclear deterrent without nuclear explosive testing. For the last 20 years, this has been proven to be possible.

7.1 Summary of Existing Capability Needs for ICF/HED

The June 2014 Ten-Year HED Science Strategic Plan identified capabilities needed for stockpile stewardship. These include capabilities in the areas of hydrodynamics under HED conditions, material properties under extreme dynamic conditions, nuclear physics, TN fusion and burn physics (platforms and diagnostics delivered by the ICF Program), radiation transport and interactions of radiation with matter, and neutron, gamma-ray, and x-ray radiation sources for nuclear survivability and vulnerability assessments. NNSA's ICF/HED portfolio addresses these capabilities. Currently, some are sufficient and some are lacking.

7.2 Changes in the Nuclear Security Environment That Affect Current Thinking

The establishment of the SSP brought about the obvious question of whether the Nation could maintain a safe, secure, and effective nuclear deterrent without nuclear explosive testing. For the last 20 years, this has been proven to be possible. Today, in addition to continuing this legacy, additional considerations in the nuclear security environment directly affect how DOE/NNSA think about ICF/HED-related capability improvements. These considerations include component aging, increasing preference for reuse or refurbishment of components, environmental concerns that affect manufacturing capabilities, increasing nuclear proliferation, and a workforce that no longer has direct nuclear explosive testing experience. Other concerns that directly impact the way NNSA thinks about future ICF/HED science capability enhancements include:

- ICF/HED capabilities are routinely requested by a growing set of non-DP nuclear security users.
- The nuclear survivability community has lost capabilities over the last 20 years. That community is looking for ways that the ICF/HED portfolio may be used to reconstitute a modern capability to meet changing requirements.

- ✧ Laboratory ignition has proven elusive. Ignition remains a major goal. "High yield" is still a program requirement and requires the pursuit of a balanced program in TN burning plasmas.
- ✧ Adversaries and near-peers are catching up and setting bold goals in ICF and HED science.
- ✧ The existing infrastructure is aging, and attracting and retaining stewards at the NNSA laboratories is becoming more difficult.

7.3 Summary of ICF/HED-Related SSP Needs for the Next 20+ Years

In addition to the activities detailed in the Ten-Year HED Science Strategic Plan, NNSA mission planning efforts over the last 18 months have identified a number of capability gaps in ICF/HED. These include:

- ✧ new experimental and computational platforms, diagnostics, and data analysis techniques to probe boost-related physics,
- ✧ new experimental and computational platforms and facilities to explore high-fidelity dynamic materials science on high-hazard materials serving multiple missions,
- ✧ new experimental and computational platforms and potentially new facilities to probe threat-relevant outputs, environments, and effects regimes motivated by emerging capabilities that may impact nuclear survivability requirements,
- ✧ new experimental and computational platforms, and potentially new facilities to create and apply multi-megajoule fusion yields per the Directors' letter, and
- ✧ new experimental and computational platforms, diagnostics, and potentially new facilities to train and test weapons designers in regimes relevant to secondary performance.

In 2016, Defense Programs seeks to develop detailed SSP plans for the next 20+ years that will include those associated with ICF/HED capabilities.

In 2016, Defense Programs seeks to develop detailed SSP plans for the next 20+ years that will include those associated with ICF/HED capabilities.

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