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Addressing Common Technical Challenges in Inertial Confinement Fusion

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Addressing Common Technical Challenges in Inertial Confinement Fusion Workshop, June 2016, Santa Fe, New Mexico. [Photo by Adam Shipman, Los Alamos National Laboratory]

Addressing Common Challenges During ICF Implosions

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Summary

The implosion phase for Inertial Confinement Fusion (ICF) occurs from initiation of the drive until just before stagnation. Evolution of the shell and fusion fuel during the implosion phase is affected by the initial conditions of the target, the drive history. Poor performing implosions are a result of the behavior that occurs during the implosion phase such as low mode asymmetries, mixing of the ablator into the fuel, and the hydrodynamic evolution of initial target features and defects such as the shell mounting hardware. The ultimate results of these effects can only be measured at stagnation. However, studying the implosion phase can be effective for understanding and mitigating these effects and for of ultimately improving the performance of ICF implosions. As the ICF program moves towards the 2020 milestone to "determine the efficacy of ignition", it will be important to understand the physics that occurs during the implosion phase. This will require both focused and integrated experiments. Focused experiments will provide the understanding and the evidence needed to support any determination concerning the efficacy of ignition.

The ICF program follows a hypothesis-driven, experimental approach consisting of three major elements:

1. *Focused-platform experiments* provide direct measurements of instabilities and their potential effect on ICF implosions. Current focused experimental platforms include inflight shape measurements [1], hydrodynamic growth experiments [2], measurements and visualization of the engineering features with imaging [3] and spectroscopy [4], etc. However, basic experiments designed to specifically test physics models would add great value to develop and demonstrate our understanding of the hydrodynamics during ICF implosions.

2. *Focused DT implosions* at particular ρR and V, provide more quantitative understanding of relative importance of critical ICF parameters while varying them one at a time [5,7,8]. Such parameters can include low-mode asymmetries, high-mode instability growth, fuel preheat, magnitudes of large engineering features.

3. *Performance scans of layered DT implosions* as functions of fuel compression (ρR) and implosion velocity V provide a broad look at the performance trends vs major ICF parameters such as ρR and V [7,8].

It is crucial to develop *appropriate* diagnostics to conduct the experiments described above. Such diagnostics include optical, x-ray, nuclear, and particle diagnostics. The focused platform experiments provide a basic benchmark of key physics models in the codes. Confidence in these individual models is needed to have confidence in the use of the codes to untangle the integrated physics. Similarly, focused DT implosion experiments are needed to isolate the correlation between physics parameters and their effect on performance. These two types of experiments provide an understanding of the performance degradation and the sensitivity to critical parameters. Finally, DT scaling experiments test the integration of our understanding of ICF implosions, as well as progress towards ignition.

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Common challenges

To understand the common implosion phase challenges across ICF approaches, the subject was divided into four high level focus areas:

- Initial conditions/adiabat/preheat
- Mix
- Implosion efficiency
- Low-mode asymmetries.

Consideration of each focus area began with a focused discussion of each ICF approach, Laser Direct Drive (LDD), Laser Indirect Drive (LID), and Magnetic Direct Drive (MDD), followed by an identification common challenges. The most impactful cross-cutting themes were apparent and became the common challenges listed below:

Common Implosion-Phase Challenges

- What are the sources of low mode asymmetries and how do they affect the implosions?
- How is the shell morphology, i.e. shell mass distribution, affected by implosion adiabat and decompression? What impact does this have on hot spot pressure?
- Are the late time acceleration and deceleration phase hydro-instabilities consistent with models and what are their effects on the implosions?
- What is the impact of defect hydrodynamics on implosion performance?
- Can the effects of LPI be mitigated for all ICF approaches?

In addition there were several minor cross cutting issues that were not believed to have a high impact at this time, but that might rise in relative importance as progress is made against the challenges listed above. These minor issues included

- Characterization of the target just prior to firing the system, ways to keep the target clean, and the use and development of cryo-platforms
- Effect of beta decay on shell
- Dynamic property changes
- Asymmetric preheat of the shell

A plan to address the common challenges included the activities listed below. While there are many other recommendations included for each common challenge listed in this white paper, these seemed to be the most universal.

Recommended Actions

- Characterization of the target just prior to firing the system, ways to keep the target clean, and the use and development of cryo-platforms
- Effect of beta decay on shell
- Dynamic property changes
- Asymmetric preheat of the shell

Common Challenge 1: Identification and mitigation of low-mode asymmetries and understanding of their effect on the fuel assembly

Recommended Actions

- Improve diagnosis of asymmetries in current implosions using Compton imaging, higher resolution (space and time) in-flight imaging, and multi-frame tomography.
- Test shimmed or deliberately perturbed implosions, both as a low-mode asymmetry diagnostic and as a mitigation strategy for asymmetries.
- Improve modeling capability (resolution and physics models) to better understand sources of asymmetry.

Background

Low-mode implosion asymmetries can degrade implosion performance; however this inference relies largely on simulation, with little direct evidence of the effect of these asymmetries on integrated observables, such as neutron yield. For indirect drive implosions thee asymmetries are thought to be caused by time-dependent asymmetries in the hohlraum radiation drive [1,2]. They have been measured in NIF implosions early in time using self-emission imaging and multi-axis VISAR, in-flight using backlit imaging, and during stagnation using self-emission imaging. However, during stagnation, only the hot spot is currently imaged in a time-dependent fashion, with the dense shell remaining invisible. For laser direct drive similar long-wavelength asymmetries can be caused by beam imbalance, mis-pointing, and target offsets [3]. Diagnosing these asymmetries in direct drive implosions has so far been even more limited than for indirect drive. For magnetic direct drive they can result from correlation of instabilities in the imploding metal liner into longer wavelength structures defined by the magnetic field orientation [4]. Structure in the hot stagnated fuel is measured through time-integrated self-emission imaging. Liner asymmetries are diagnosed through radiography on separate experiments that do not pre-heat and decelerate against the fuel, making it difficult to directly connect implosion structures with fuel column asymmetries.

Plan to address

Better diagnosis of the asymmetries present in implosions is clearly called for in all approaches. This needs to emphasize better time and space resolution; the ability to effectively characterize 3D structures, the ability to track how implosion structures imprint on the hot fuel, and to what extent this actually affects confinement and neutron production. Desired diagnostics include Compton imaging of the imploded core, multi-frame tomography of the shell or liner and fuel, orthogonal neutron imaging, and multi-axis, high-resolution (< 5 μm and < 10 ps (~100 ps for MDD)) in-flight shell/liner imaging. In simulation, upgraded physics models are required for the predictive modeling of drive asymmetries. For laser indirect drive, these should better capture hohlraum plasma evolution in near-vacuum or intermediate gas fill hohlraums, to mitigate the artificial numerical stagnation feature between the hohlraum wall and capsule blow-off that prevents accurate simulation of laser propagation to the wall. For magnetic drive these should better capture the growth and evolution of implosion instabilities in large scale 3D calculations, and better capture the kinetic or non-ideal MHD behavior of low density plasmas. Continued improvements in grid resolution, opacity and EOS models, as well as LPI modeling are necessary to better understand the time-dependent sources of hohlraum asymmetries, coupling between driver and shell asymmetry, and asymmetries introduced by non-uniform laser energy deposition in the preheat of magnetic direct drive targets. Common to all approaches is the need to develop and improve our simulated diagnostic capability to enable effective comparison between experiment and simulation.

Current efforts to mitigate low-mode asymmetries for indirect drive focus on reducing the source of asymmetries from the hohlraum by increasing the case-to-capsule ratio (CCR) and reducing the laser pulse length. Alternate approaches include applying deliberate asymmetries to the capsule ("shimming")[5,6] or picket [7] which if tuned to the correct amplitude, could substantially cancel out those asymmetries yielding a higher performing implosion. Initially applying deliberate asymmetries in a similar way could benefit all approaches by measuring the effect on final hot fuel asymmetry and experimentally establishing to what extent low mode asymmetries actually affect performance and yield.

Finally, though challenging in integrated implosion experiments, efforts should be made to show a clear experimental correlation between measured low-mode asymmetries and performance metrics, in particular neutron yield.

Impact of successfully addressing low-mode asymmetries

Current simulations suggest that totally eliminating hohlraum asymmetries from current NIF implosions could result in factors-of-several improvements in neutron yield. Similar improvements are projected for direct drive implosions on OMEGA when target offsets and beam imbalance are zeroed, and are potentially realizable for magnetic direct drive if it is established that such asymmetries are degrading the yield.

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Common Challenge 2: Effect of shell morphology and decompression on coupling energy to fuel

Recommended Actions

- Measure late time inbound shocks.
- Assess new diagnostics for measuring the shell mass distribution.
- Specify EOS, opacity, conductivity needs for measuring shell radial morphology.

Background

The coupling of energy to the fuel in an ICF implosion depends significantly on the kinetic energy density of the shell. The shell transfers its energy to the fuel via PdV work. Mechanisms that reduce this transfer of energy lead to inefficiencies that can ultimately prevent the implosion from achieving the goal of thermonuclear burn. One mechanism [1] that has been shown to decrease coupling is the shell morphology, i.e. mass distribution. When the shell decompresses or changes its mass distribution, the kinetic energy density can decrease that can decrease the transfer of energy to the fuel. This can occur when for instance the inner portion of the shell forms a foot prior to peak compression. Such behavior may be the cause of experimental observations such as the formation of the hot spot at larger radii than expected in laser direct drive or the change in performance between coast/no coast implosions for laser indirect drive. In magnetic direct drive, the radial expansion of the liner is observed in experiments, and simulations show the expansion affects the implosion performance. Understanding how the shell morphology evolves throughout an implosion is important to understanding how this impacts the transfer of shell kinetic energy to the fuel.

The evolution of the shell morphology is believed to be a result of the shell adiabat. Understanding the shock behavior in the shell is needed to understand the shell adiabat evolution. There has long been the hypothesized “N+1” shock for laser indirect drive. Since the VISAR is unable to measure shock speeds above ~150 km/s, such a shock that occur after that from the main drive is not observable by optical means. Shocks reflecting in the shell will change the shell adiabat and thus the morphology. There is also the shock/rarefaction history at the interface that can change the shell morphology. In MDD, the drive pressure’s history, radial distribution, and overall coupling can affect the liner/shell morphology. Additionally, it is unclear how the dielectric coating, which is applied to the liner's outer surface for enhanced implosion stability, affects the liner's radial morphology in flight.

Plan to address

To measure key quantities associated with the shell adiabat and morphology, there are two key measurements in which development work is required. The first is associated with the shell adiabat. A technique to measure the "N+1" shock must be developed using diagnostics such as VISAR, SOP, or streaked phase contrast, for example [2]. The second is the ability to measure the shell mass distribution directly. This will require the development of a novel approach to this problem such as streaked phase contrast imaging[1]. Due to the inflight shell thickness, ~ 40 um, and the high implosion velocity, ~ 370 km/s, high spatial and temporal resolution imaging will be needed, 10 ps, 5 um resolution. In addition, MDD will require improved drive pressure measurements.

To understand the shell morphology evolution, we will also have to develop improved theory and simulation capability. Because the shell expansion depends on the release wave, better release EOS for ICF ablator materials is needed. There are also opportunities to use current measurement techniques for the shell with backlight radiography such as in the 1D Convergent ablator platform on NIF. However, better opacity corrections are needed to get accurate shell mass distribution for meaningful comparisons between simulations and data. One action that would help understand the evolution of the shell morphology is how preheat affects the shell adiabat. Simulations in 3D could guide the direction for understanding the role of asymmetric preheat in the shell morphology. For MDD, better current models for the power feeds are needed to understand the drive pressure history.

Impact of successfully addressing shell morphology degradation

Current simulations suggest that the evolution of the shell morphology could reduce implosion performance by roughly a factor of 2. If we can understand the evolution of the shell morphology and maintain compression, we should realize significant gains in performance.

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Common Challenge 3: Hydrodynamic instabilities at all unstable interfaces during late time acceleration and deceleration phases of ICF implosions

Recommended Actions

- Develop high resolution spatial and temporal diagnostics, experimental platforms, and targets (including localized dopants).
- Measure instability growth of engineering features, defects, and other seeds, especially near peak velocity and peak compression.
- Study controlled "test" defects in focused platforms, measure their effects in integrated layered DT experiments, and validate their theoretical and computational modeling.
- Extend modeling of defects to better handle fine structure and directly capture injection.

Background

Hydrodynamic instability growth was among the primary reasons for substantially degraded performance of indirect-drive implosions during the National Ignition Campaign (NIC) [1]. The combination of seeding and growth of local imperfections such as capsule mounts (or "tents") [2,3] and three-dimensional broadband modulations [3] were measured to be larger than initially expected in CH implosions on NIF [4]. The instability growth of high-mode modulations, including tents, was shown to be a significant cause of the degradation in "low-foot" implosions during NIC, as demonstrated during subsequent "high-foot" [5] and "adiabat-shaping" campaigns [6,7].

In indirect- and direct-drive ICF, fusion yield is particularly sensitive to late-time hydrodynamic instabilities that grow on the inner surface of the spherical DT-ice layer. The "seeds" for this instability are provided by the roughness of ice layer itself as well as the surface and drive non-uniformities that "feed through" from the ablator during the acceleration phase of the implosion process. Once these inner-surface perturbations become nonlinear, a significant fraction of the fuel shell's kinetic energy can be diverted from inward radial motion to lateral and outward radial motion, which reduces the energy available to form and compress the hot spot. Additionally, the penetration of RT "spikes" into the hot spot decreases the fusion volume and increases the surface-to-volume ratio of the hot core. This, in turn, increases losses due to thermal conduction, lowering the hot-spot temperature. In the direct-drive (OMEGA) platform, high-mode instability growth leads to ablator-fuel mix and significant yield degradation in low adiabat implosions [8,9]. If instability growth is severe enough and ablator material mixes into the hot spot, radiation losses will further reduce the hot-spot temperature and can completely quench the implosion. Thus, late-time hydrodynamic instabilities are detrimental to the performance of both indirect- and direct-drive ICF for several reasons: 1) they increase radiation losses from the hot spot; 2) they increase residual fluid motion in the compressed fuel (which leads to a less efficient conversion of shell kinetic energy to thermal energy in the hot spot); and 3) they result in less efficient volume compression of the fuel due to shape irregularities.

The same considerations generally hold true for the MagLIF approach to magnetically-driven ICF, although overall performance in that scheme is apparently less sensitive to late-time mix than to the early-time variety, which is induced either by laser preheat or shock breakout from the liner into the fuel. There are at least two possible reasons for this. The first is that the laser-preheating phase in MagLIF occurs 50-60 ns prior to the stagnation time and the second is that the magnetic field provides at least some stabilization to the growth of unstable axial modes.

It should be noted, however, that this axial field in MagLIF provides no stabilization to the growth of azimuthal modes, which can grow aggressively at late times. Despite the importance of these modes to the symmetry of the implosion, azimuthal modes have never been directly imaged in a MagLIF experiment. Information on azimuthal-mode growth has been inferred only indirectly from side-on imaging. For example, in cases with a bare MagLIF liner, side-on imaging has shown that the topology of the hot fuel is possibly ribbon-like with a slight helical twist (although in very recent experiments, it has been possible to achieve a straight and uniform hot-fuel column by adding a dielectric coating to the outer surface of the liner). Three-dimensional simulations using the GORGON MHD code suggest that current MagLIF designs may be most susceptible to low-mode azimuthal asymmetries with mode numbers of about 2–4.

The effect of *high-mode* asymmetries on MagLIF target performance and fuel assembly, however, is a subject that is not as well characterized experimentally or understood theoretically. It is generally believed that current numerical algorithms are simply incapable of simulating accurately the growth of high-mode asymmetries and the ensuing mix states they generate. This is true for MagLIF as well as the indirect- and direct-drive approaches to ICF. In light of this common deficiency, there is an urgent need in ICF research to develop more advanced mix models and to incorporate them into existing ICF design codes. Unfortunately, though, very little experimental data on late-time hydrodynamic instabilities and mix is available to benchmark such mix models. Therefore, there is a concurrent need to develop experimental platforms for studying the relevant physics of late-time instability growth and mix-width evolution in an easily diagnosable way.

Plan to address

Significant efforts are required to further understand and mitigate effects of hydrodynamic instabilities in all three approaches. Better diagnosis of the instability growth at outer surface, ablator-fuel interface, and inner fuel-gas interface is clearly required, especially near peak velocity and peak compression. This includes multi-axis and high-resolution (< 5 mm and < 10 ps) in-flight imaging, spectroscopy, and backlighting of the 3-D modulations, as well as multi-frame tomography of the compressed cores. This also includes developing new capsules with localized dopants to include x-ray spectroscopic and radiochemistry diagnostics and techniques. Inner foam layers (including doped spectroscopic layers) should also be considered as surrogate DT fuel layers in direct and indirect drive ICF to visualize the fuel and better understand sources of non-uniformities near peak compression. New high-spatial and high-temporal resolution diagnostics should be built to allow such experiments.

For all three approaches, but especially for the MagLIF, one can study high-convergence, high-pressure, high-$P\tau$, decelerating and stagnating phenomena using cold dense fuel in a cylindrical geometry. To address the instabilities at the ablator-ice interface with both direct and indirect drive, new mix platforms should be developed to measure ablator-ice mix directly. Significant efforts should be made to show a clear experimental correlation between measured instability growth and performance metrics in integrated implosion experiments, in particular neutron yield and ρR. This could include applying intentional surface or interface roughening for layered implosions. Finally, the number of nuclear diagnostics for fuel morphology and modulations such as FNAD's needs to be increased and their accuracy improved by ~2x. Neutron imaging lines of sight for primary and down-scattered neutrons should be built on NIF in three orthogonal directions

Impact of successfully addressing hydrodynamic instabilities

Current simulations suggest that significantly mitigating high-mode instabilities in current NIF implosions could result in factors of several improvements in neutron yield. Similar improvements are projected for low-adiabat, direct-drive implosions on OMEGA when instability growth is mitigated.

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Common Challenge 4: Understand initial non-uniformities and seeds for hydrodynamic instabilities including engineering features and defects

Recommended Actions

- Develop high spatial and temporal resolution x-ray diagnostics, experimental platforms, and targets (including localized dopants).
- Improve accuracy of current nuclear diagnostics for fuel morphology and modulation measurements, increase their numbers, and develop multi-axis neutron imaging diagnostics.
- Measure instability growth of 3-D modulations and mix especially near peak velocity and peak compression at various unstable interfaces.
- Vary and measure effects of instabilities in controlled, focused platforms, then measure their effects in integrated layered DT experiments.
- Validate measured instability growth with theoretical and computational modeling.

Background

Today there is general acceptance that defects were among the primary reasons that substantially impacted the performance of indirect-drive implosions during the National Ignition Campaign (NIC) [1]. Local imperfections such as capsule mounts (or "tents") [2,3] and fill tubes [4] were measured to be larger than initially expected in implosions on NIF [5]. The instability growth of high-mode modulations, including tents, was shown to be a significant cause of the degradation in "low-foot" implosions during NIC, as demonstrated during subsequent "high-foot" [6] and "adiabat-shaping" campaigns [7,8]. Unexpected modulations due to oxygen uptake can also create significant non-uniformities (or "seeds") in capsules that can compromise indirect-drive and direct-drive implosions [3,9]. In the direct-drive (OMEGA) platform, particulate defects are similarly leading to ablator mix in low adiabat implosions [10,11]. Spectroscopic data from the magnetized platform shows support materials and liner are being injected into the heated fuel.

Plan to address

Significant efforts are required to further understand and mitigate effects of initial seeds and engineering features. Such efforts should include further stabilization of initial seeds in the initial, ablative Richtmyer-Meshkov (ARM) phase of implosions. This should include optimizing the choice of drive pulse shape and outer ablator material using the results of growth of large pre-imposed modulations after first shock transit. Developments of alternate capsule mounts including polar tents, cantilevered fill tubes, outer foam layers, etc., should continue for mitigating detrimental effects of the engineering features and initial seeds. In direct drive, developments of clean target procedures during layering and mitigation of the instability growth should be major parts of the program. As outlined below, moving towards understanding of defects raises numerous commonalities of diagnostic needs, platforms and computational capabilities among the three ICF approaches.

Better diagnosis of the instability growth of engineering features and other seeds in current implosions is clearly required. This includes multi-axis and high-resolution (< 5 μm and < 10 ps) in-flight imaging, spectroscopy, and backlighting of the features, multi-frame tomography of the compressed cores especially near peak velocity and peak compression. This includes developing new capsules with localized dopants to include x-ray spectroscopic and radiochemistry diagnostics and techniques. Improvements in modeling of defects are required to better handle fine structure and directly capture injection (e.g. the use of adaptive mesh resolution, Eulerian hydrodynamics simulations). Finally, though challenging in integrated implosion experiments, efforts should be made to show a clear experimental correlation between measured growth of "test" engineering features and performance metrics, in particular neutron yield and ρR.

Impact of successfully addressing engineering features and target imperfections

Current simulations suggest that totally eliminating or mitigating engineering features in current NIF implosions could result in factors of several improvements in neutron yield. Similar improvements are projected for low-adiabat, direct-drive implosions on OMEGA when target dust and other seeds are mitigated.

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Common Challenge 5: Laser plasma interactions—laser energy coupling and instabilities

Recommended Actions

- Develop a means to share information, tools, and expertise across the ignition laboratories.

Background

While laser plasma interactions were not included as part of the workshop, the issue manifested itself several times during the implosion discussions. Laser plasma interactions are a common challenge to all three approaches. Laser Plasma Instabilities play a critical role in coupling and symmetry for LDD and LID. In order to understand low mode asymmetry, shell adiabat, and mix, information from laser plasma interaction of the hohlraum for LID and shell for LDD is needed. Coupling preheat laser energy to the target for MDD is crucial for the success of the current approach, MagLIF. In addition, filamentation of the beam in the gas cylinder for MDD may also seed hydrodynamic instabilities on the inner surface of the shell through non-uniform ablation. Backscattered laser light also results in slower progress to ensure machine safety and avoid high refurbishment costs. Advances in our understanding of laser matter interactions would greatly benefit all three ICF approaches for these reasons.

Addressing Common Challenges in Stagnation

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Summary

Stagnation, the period during an Inertial Confinement Fusion (ICF) implosion where the kinetic energy reaches a minimum and the thermal energy ideally reaches a maximum, has many commonalities across the three main approaches to ICF; Laser Indirect Drive (LID), Laser Direct Drive (LDD), and Magnetic Direct Drive (MDD). While there are significant differences in the driver technologies, implosion parameters, and geometry (ex. spherical vs. cylindrical convergence), there are many synergies in the diagnostic techniques and simulation methods that would benefit from an enhanced collaboration across the National program. A panel of experts in the field across all three ICF approaches met for a 5-day workshop to discuss the relevant physics, identify the common challenges, and form a set of recommended actions in order to realize this enhanced collaboration and promote deeper understanding of the relevant stagnation physics. The common challenges identified by this panel are:

Common Stagnation-Phase Challenges

- Understand the hotspot conditions in the context of ignition metrics.
- Identify the magnitude and origins of mix and quantify the radiative loss.
- Identify experimental signatures for each degradation mechanism from simulations and validate against experiments.

The recommended actions proposed by the panel to address these common challenges are (listed in approximate priority order):

Recommended Actions

- Clarify the meaning of and observables for pressure and confinement time.
- Form a working group on mix analysis and electron Temperature.
- Form an image analysis working group to share techniques and identify synergies.
- Identify and test peer-reviewed basecamps for each approach.
- Catalog failure modes and associated signatures.
- Develop common simulated diagnostics to connect simulations to experiments.

Background

Stagnate /'stag,nāt/: Cease developing; become inactive or dull.

This is how stagnation is defined in the Oxford English Dictionary. Cleary, we have a different definition in mind for ICF. In the context of ICF, we have traditionally thought of stagnation 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 'stagnation' plasma remains dynamic and is far from being either inactive or dull. There are many processes occurring during this critical phase of the implosion history including multi-dimensional flows, species mixing, fusion reactions, ion-electron energy exchange, and radiative cooling. These processes are coupled in many ways, and their magnitude and evolution are a product of the previous phases in the target history; the preconditioning, driver-target coupling, and implosion phases. Subsequently, it is difficult to change anything about the plasma during the stagnation phase of a fully integrated, high performance ICF implosion.

The efforts of the Stagnation Priority Research Direction are thus largely about measurements and interpretation. The goal is to accurately diagnose the real state of the stagnation plasma and, through comparison to modeling, form hypotheses regarding the necessary changes in the previous phases required to form a more ideal stagnation state. By 'state' we mean the particle (ion, electron, and fusion product) energy distribution as a function of three-dimensional space and time. As these cannot be directly measured in all four dimensions, we instead form the most complete picture possible through an ensemble of diagnostics that each integrate over some subset of these dimensions folded through an instrument response function. This state also cannot be easily simulated in all four dimensions with complete physics, so we typically rely on models that integrate over a subset of 3-D space and use approximations to the complete physics (Maxwellian energy distributions, flux-limited conductivities, simplified opacities, mix models, *etc.*).

The present understanding of the stagnation phase in the three ICF approaches is described in detail in the report from the National Implosion and Stagnation Physics Working Group. In general, all three approaches have trouble understanding the cause of deviations between experiments and simulations, particularly at the high convergences believed to be required to achieve ignition at the driver energies available today or in the foreseeable future. The common challenges described below have been identified to help understand these deviations and close the gap between simulated and measured ICF implosions.

Common challenges

In order to divide the issues of ICF stagnation and identify the highest priority common challenges across the three approaches, the subject was divided into 4 areas: Stagnation Pictures, Hotspot Morphology and Kinetic Energy, Shell Morphology and Kinetic Energy, and Mix. Through these discussions, the working group identified the following four challenges as being relevant for all three modalities, amenable to attack over the next several years, and requiring the coordinated efforts of the national program:

1. Understand the hotspot conditions in the context of ignition metrics.
2. Identify the magnitude and origins of mix and quantify the radiative loss.
3. Identify experimental signatures for each degradation mechanism from simulations and validate against experiments.

The next few sections describe these challenges in terms of what we know today, what puzzles us, and what new experiments, diagnostics, and/or simulations are required to deepen our understanding of these issues. The path forward is further summarized into a series of recommended actions that are described in the final section of this document.

Common Challenge 1: Understand the hotspot conditions in the context of ignition metrics

Background

Stagnation has traditionally been thought of as the state of maximum fuel compression where the implosion kinetic energy has been efficiently converted into hot-spot internal energy. Ideally, this process creates a stagnation phase when the hot-spot temperature reaches a maximum and the Residual Kinetic Energy (RKE) reaches a minimum. In reality, the 'stagnated' hot spot generally remains highly dynamic and three-dimensional (3D) in nature where RKE can be significant and many processes are still evolving. To control and mitigate the 3D behavior, a physical understanding of the 'stagnated' hot spot is formed through an ensemble of highly integrating diagnostic observables described by 3D models that necessarily use some approximations to the true physics. Understanding these models and their applicability to the 3D and highly dynamic stagnation phase is an important factor determining whether sufficient self-heating and ignition can be achieved or what is required to do so. This is true for all three ICF approaches. In this context, understanding the stagnation pressure, the hot-spot ρR, thermal ion temperature, and fuel magnetization (for MDD) are also key in assessing the ignition margin and scaling.

3D models for self-heating and ignition are, however, very complex. The mechanical work of the imploding shell, which depends strongly on the 3D shell morphology and integrity, is reduced if the shell cannot effectively compress the hot spot symmetrically, leading to larger minimum volumes for the hot spot, more RKE in the shell at bounce, and lower PV energy and pressure in the hot spot. If the shell is not intact, hot-spot material may even leak through perforations reducing hot-spot areal density (ρR) and ion temperature. In the case of MDD stagnation, m=0, m=1, or short-wavelength 3D instabilities may play a similar role in reducing hot fuel volume and confinement time. Conduction losses may be enhanced by the 3D morphology of the hot region in all approaches, cooling its edges and shrinking the hot volume. A key criterion for achieving ignition in LID and LDD implosions is to maintain temperatures in excess of ~4.3 keV in order for alpha heating to exceed the radiative loss. While fuel magnetization can trap fusion products and reduce requirements on ρR for MDD, similarly high ion temperature is required, and gradients in the fuel may reduce the fusion volume.

Germane to our efforts in understanding the characteristics of the hot-spot, we need to ultimately address why the hot spot is underperforming simulation predictions. Performance can be quantified by either yield or by more sophisticated metrics, including pressure, Chi, or ITFX [1]. In any case, experiments fall short of simulated predictions for all ICF approaches. In LID and LDD implosions, we have observed two phenomena in particular that suggest issues with the hot spot: high apparent ion temperatures and a 3D asymmetric shape. The hot-spot ion temperature is typically higher than predicted by hundreds of eV, but it is not accompanied by an associated yield increase. Recent theory [2-3] shows that hydrodynamic flow (variance in velocity) can increase the measured apparent ion temperature. Temperature measurements can also vary with line of sight. Such variation is routine in LDD implosions and is seen occasionally in LID implosions. Moreover, the measured apparent DD ion temperature is generally lower than the apparent DT ion temperature (these temperatures are determined from the DT and DD neutron spectral broadening), which cannot be entirely captured by modeling. Tritium is not presently available on the Z Facility, and would be required to compare these observations for MDD. Developing measurements of electron temperature should eventually constrain the thermal part of the measured apparent ion temperature, helping to separate thermodynamic effects from hydrodynamic effects.

The hot spot is also highly 3D asymmetric in nature in LID and LDD implosions. X-ray emission images from multiple lines of sight clearly show that the hot spot is non-spherical. Time resolved imaging also indicates that the hot spot evolves dynamically, or swings, from one conformation to another. This dynamic behavior damages the stagnation phase, leaving flowing material and RKE in the hot spot and cold shell. The remaining flow and RKE waste energy that could otherwise have been converted into useful hot spot internal energy. Other asymmetries, such as thin spots or holes from engineering features additionally degrade hot-spot performance as they facilitate additional energy losses. Apparent 3D structure is also seen in x-ray images of cylindrical MDD implosions, though additional measurements are needed to determine whether this results from variation in hot-spot fuel temperature and density or from axial variations in the absorption of the x-rays as they pass through the unstable liner.

As the hot-spot pressure and ρR are difficult to directly measure, they are inferred from a combination of data including x-rays and neutron images, neutron spectra, DT and DD yields, time duration of x-ray and thermonuclear gamma emission, and x-ray yields and spectra. Often these data give ambiguous or conflicting results, which clearly impact our understanding. As previously discussed, the presence of RKE in LID and LDD implosions is an effect that can significantly distort the interpretation of the DD and DT neutron spectra, resulting in deduced apparent ion temperatures that significantly exceed the thermal temperature. Note that RKE in MDD implosions is estimated to not affect the apparent ion temperature, but it may still affect energy balance and fuel conditions at stagnation. Likewise, x-ray spectral emission can be influenced by mix, and the spectrum and spatially varying x-ray emission can be distorted by absorption as x-rays leave the implosion. Electron temperatures inferred from impurity K-shell line spectra and from continuum slope differ in MDD plasmas, suggesting that gradients and mix may both affect data interpretation. The question is what temperature should be used when inferring the ignition metrics when these data disagree?

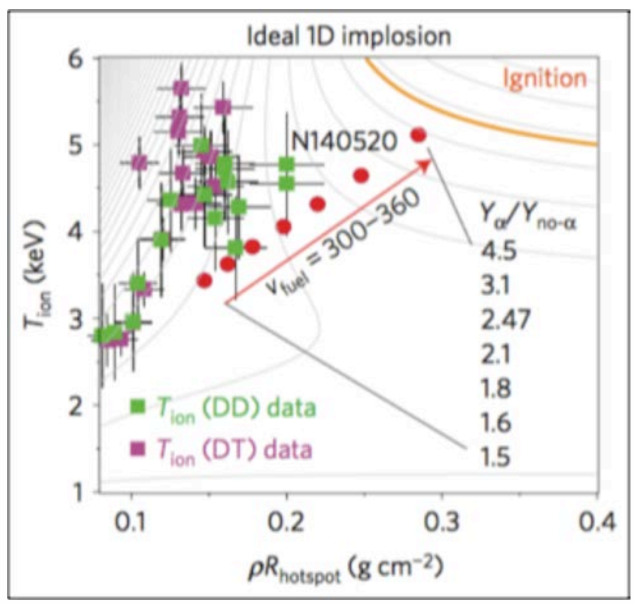

Figure 1. 3D implosion morphology and implosion data located in a parameter space relevant to ignition. [Hurricane, et al., Nature (2016).]

Resolving and clarifying the multiple temperature measurements is key to a more thorough understanding of the hot spot (and global implosion) performance. For example, Figure 1 illustrates the inferred hot-spot ρR versus apparent ion temperature for a series of high-foot implosions at the NIF. These implosion parameters were determined from measured DD and DT ion temperatures, yields, hot-spot radius and burn duration. Both the apparent DD and DT ion temperatures are higher than expected, while the hot-spot ρR is substantially lower. If the true thermal ion temperature is lower than the apparent DT and DD ion temperature, then an overestimation of pressure (in direct proportion to the temperature error) and an underestimation of the hot-spot ρR (as the square of the temperature error) is made. Our goal is to understand the scaling to the upper right corner in Figure 1 labeled “ignition”, where the hot-spot self-heating would overcome both radiative and conduction losses at minimum volume. If the hot spots are in fact colder and denser than expected, then the scaling to ignition is more difficult. If other mechanisms are also at play, like hot-spot material leaking through perforations, then these extra losses must be incorporated into 3D ignition metrics.

We need to develop ignition metrics that are cognizant of 3D effects and work to reconcile differences with 1D metrics. In addition, we need to achieve robust measurements of hot-spot ignition metrics such as hot-spot areal density and stagnation pressure, along with fuel magnetization for MDD and reconcile the differences between the interpretations from various diagnostic approaches.

Plan to address

Although the diagnostic observables obtained to date have been essential for understanding the hot-spot conditions and for guiding the different programs towards more ignition-relevant conditions, the current diagnostic suite on the different facilities only provides a limited set of temporal and spatial information about the hot-spot conditions. In the context of optimizing the hot-spot conditions, the effect of RKE is also an outstanding issue that needs to be addressed. Simply stated, if the RKE of the fuel and ablator/liner during assembly is not effectively transferred to hot-spot internal energy, the ignition-relevant conditions will not be achieved. The magnitude and evolution of the hot-spot conditions, including the RKE, must be quantified with higher fidelity through spatially resolved quantities such as electron density, $n_e(r,t)$, electron temperature $T_e(r,t)$, and neutron yield $Y_n(r,t)$ as well as spatially averaged, temporally resolved quantities such as the apparent ion temperature $<T_i(t)>$ and $Y_n(t)$. To obtain this information we must develop the next-generation diagnostics and experiments shown in Table 1.

In addition to improved diagnostics, 3D simulations must also be used to model the inherently asymmetric implosions. Though expensive and time consuming, these simulations are valuable for highlighting possible mechanisms for the performance degradation, especially when the mechanisms for the performance degradation are not completely understood. High-fidelity 3D simulations can guide development of analytic theory to explain how asymmetries and other loss mechanisms affect the hot-spot conditions in ignition-relevant implosions. Using theory, one can then set goals and specifications for symmetry, uniformity, and timing of implosions to produce the highest possible performance.

In simulations, conditions can also be altered to highlight particular failure mechanisms that degrade implosion performance. The results of these simulations should be post-processed to create synthetic diagnostic data to identify specific signatures or correlations in groups of signatures that indicate specific failure mechanisms. High-fidelity 3D simulations are becoming increasingly available. For laser indirect-drive, they have been used to identify the level of hot-spot degradation caused by the fill tube and the capsule support tent. Increased emphasis on 3D simulations in laser direct drive will continue to yield similar benefits. 3D simulations of MagLIF implosions can quantitatively match the highly 3D x-ray imaging and radiography data, though additional work is needed to understand the actual deviation of the fuel from a local 1D/2D behavior. Validated 2D and

3D models are needed as baselines for comparison to data as experimental parameters are varied to seek improved performance.

In radiation hydrodynamics codes, many approximations are made to simplify or ignore certain physics considered relatively unimportant to provide results in an efficient and timely manner. When implosions proceed in an expected manner, these assumptions are probably well justified. However, when unexpected behavior is observed, or the conditions for which the approximations are violated, then many of the simplified models may no longer be adequate to accurately describe the behavior of all aspects of an implosion. Among the effects that are not included in detailed simulations are kinetic and plasma effects that may lead to species separation, non-Maxwellian ion distributions, and enhanced diffusion. The importance of these effects remains an area of disagreement. Theory and computations should be performed, for both well-behaved and problematic implosions to determine whether non-hydrodynamic physics can affect the behavior of ignition-relevant implosions.

Next-generation diagnostics and experiments that should be used to diagnose hot-spot conditions.

Diagnostics Near term, <2018	1. High resolution spectrometers and narrow-band imagers (KB, crystals) coupled to single line-of-sight (SLOS) detectors for hot spot shape(t), $T_e(r/z,t)$, and $n_e(r/z,t)$. 2. Multi-view neutron and x-ray imaging for assessment of 3D structure. 3. Gas Cherenkov Detectors (GCD) + pulse-dilation PMTs for $Y\gamma(t)$. 4. Co-registered Neutron and X-ray Imaging (CNXI) for shot-spot shape. 5. Ross pair temporal measurements for $T_e(t)$. 6. Advanced Radiographic Capability (ARC on NIF) for hot-spot $\rho R(t)$ and shape(t).
Diagnostics Mid-term, <2020	1. Magnetic Recoil Spectrometer (MRS) coupled to gated detectors for $T_i(t)$, $\rho R(t)$ and $Y_n(t)$. 2. High-energy narrow-band imagers (Wolter, KB, Crystal optics) coupled to pulse-dilation tubes for $T_e(r,t)$. 3. GCD on Z for burn history on MDD implosions.
Diagnostics Long-term, <2030	1. Spatially/temporally resolved neutron spectrometry $T_i(r,t)$, $\rho R(r,t)$ and $Y_n(r,t)$. 2. Time resolved hot-spot tomography (>3 views). 3. Advanced x-ray Thomson scattering (XRTS) laser probes.
Experiments Near term, <2018	1. Scans of convergence ratio and implosion velocity 2. Basecamp and perturbation experiments 3. Trace tritium on Z for $Y_n(t)$ and DT ion temperature
Experiments Mid term, <2020	1. Basecamp and perturbation experiments 2. 10:90 DT on Z

Experiments Long term, <2030	1. 50:50 D:T on Z

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Common Challenge 2: Identify the magnitude and origins of mix and quantify the radiative loss

Background

The loss of energy via radiation is unavoidable in all ICF systems. One can only strive to minimize the radiative loss rate by limiting the amount of material in the hot, dense plasma that won't contribute to the fusion process. As an example, Figure 2 shows the radiative loss rate as a function of temperature for a pure deuterium plasma compared to that from the same plasma mixed with various amounts of other materials. Depending on the mixing species, some amount of mix is tolerable as long as it doesn't increase the loss rate significantly above that expected from the deuterium. These tolerable amounts depend on the temperature and density time-history of the fusion fuel and will therefore be different for each approach.

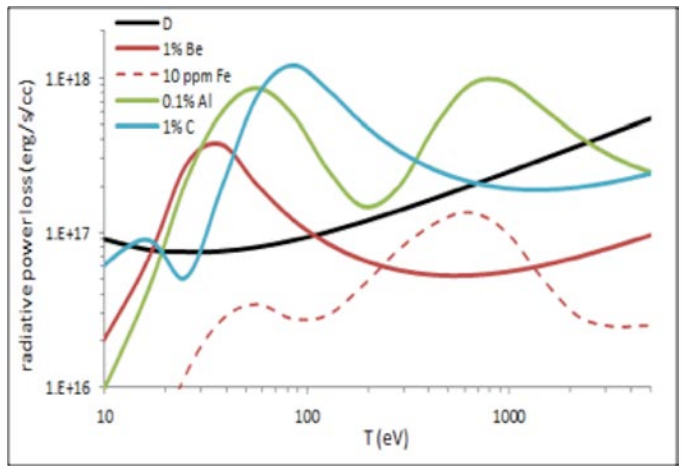

Figure 2: Calculated radiative power for a pure deuterium plasma at an electron density of $1 \times 10^{20}/cm^3$ compared to the same deuterium plasma mixed with various amounts of Be, Fe, Al, or C. [S. Hansen, private communication]

All ICF approaches have observed the negative impact of mix on the total fusion output.

LID: In the very high convergence, high-velocity, low-foot implosions studied during the National Ignition Campaign, material from the ablator was observed to penetrate the hot spot and resulted in significant loss of energy [1,2]. This mixing is believed to be caused by hydro-instabilities seeded by the capsule support tent [3]. In the lower convergence high-foot implosions, ablator mixing is not directly observed and the measured radiation output from the capsules is consistent with models that show a clean, unmixed hot spot. X-ray self-emission imaging of recent experiments with high density carbon ablators show a jet of ablator material that penetrates the fuel. This jet is believed to originate from the fill-tube. Its impact on performance—in terms of shape hot-spot/shell asymmetry or hot-spot energetics—is not yet fully understood.

LDD: In high-adiabat implosions on OMEGA, low-mode distortion of the hot spot is thought to limit the hot-spot pressure, not the mixing of ablator material into the hot spot [4]. As the implosion is modified for higher compression using a lower adiabat drive, the measured yields deviate from the simulations and the radiated power from the capsule is observed to increase [5-7]. In these low-adiabat implosions, laser imprint and capsule surface debris are hypothesized to seed hydro-instabilities that limit the convergence and cause ablator-fuel mixing [8]. Recent DT cryogenic implosion experiments use a Ge-doped plastic ablator to diagnose hot-spot mix. Mixing of ablator material into the compressed DT shell has been inferred from x-ray backlighting experiments [9]. Understanding hot-spot mix would greatly benefit from a measurement of the hot-spot radiated power.

MDD: In MagLIF implosions, mix of Be has been directly observed in the hot stagnation column [10,11]. Both the liner and the top/bottom cushions are made of Be, and it is not presently known which is the dominant source of the mix. Experiments replacing the cushion material with aluminum show a significant decrease in the neutron yield, but only when using thin laser entrance windows indicating that mix can be seeded early during the laser preheating phase. The laser entrance window itself may also be a significant source of mix, and some simulations show it can be pushed far down into the stagnation column. Mix from the liner during the laser preheating, implosion, and/or stagnation phase is also plausible, but the relative magnitudes from each phase and the impact on the radiative energy loss and the associated stagnation conditions are yet to be understood.

In each approach, it is important to understand the source(s) of mix and to quantify the radiative energy loss. The absolute radiated power is measured in LID experiments, but it needs to be consistently quantified in LDD and MDD implosions. In some cases it may not be possible to directly observe the mix, particularly if it is radiating in a photon energy band that doesn't escape the surrounding colder ablator/liner plasma. It is unknown how much of this 'dark mix' exists in any of the three approaches or whether it has a significant impact on the energetics and the resulting stagnation conditions. Another area of concern common to all approaches is in the simulation of the mix processes. 3-D features are believed to exist in all implosion types, which is a challenge to simulate with high resolution. In general, we don't know the uncertainties in our ability to simulate mix.

Plan to address

Addressing the common challenge of quantifying and controlling mix will require advances in experimental techniques, diagnostics, targets, and simulations. In all three approaches, the goal is to understand the origins of mix, the relative concentration of contaminants in the fuel, and the contribution of these contaminants to the radiative energy loss.

Quantifying the radiated x-ray power together with the burn history is the most fundamental aspect of understanding the impact of mix on the stagnation dynamics and the associated fusion process. Efforts are underway in all three approaches to develop improved diagnostics for measuring the radiated power in the high photon energy bands where the emission from the hot stagnation plasma is not absorbed in the surrounding ablator/liner. Spectrally resolving a few different energy bands in this range can also provide a measurement of the electron temperature, which is integrally connected with the radiated power and the associated mix. One key recommendation from the stagnation panel at this workshop is to ensure that the separate groups developing these multi-band power and electron temperature diagnostics share information and methods.

In other areas of diagnostic development, the ability to diagnose tracer material doped or coated into the ablator or liner is key to understanding the sources and relative concentrations of mix. This method, presently used by each ICF approach, is to put mid-Z material at a known location in the target and then spectroscopically observe the characteristic line emission to determine the absolute amount of the tracer material at different locations in the hot stagnation plasma. This approach isn't new, but deepening our understanding of the mix process requires new diagnostics and analysis methods that provide better temporal and spatial resolution. New single line-of-sight (SLOS) detectors are under development as a part of the National Diagnostic Plan that will enable multi-frame imaging and spectroscopy using advanced optics (ex. spherical crystals and Wolter optics) while achieving simultaneously high temporal (>=10 ps) and spatial (<=5 um at the target plane) resolution. The new generation of narrow-band imagers and space-resolving spectrometers enabled by these detectors will provide a high density of information that will need efficient analysis methods to interpret. A national mix working group should be formed to share ideas on experimental methods and data analysis from these types of focused experiments.

Advances in targets are required to provide the necessary options to do the tracer experiments discussed above and to decrease the impact of engineering features on the development of hydro-instabilities that promote mix. The specific development needs are approach dependent, but the fabrication and metrology methods will likely have significant overlap. High priority should be put on minimizing/removing fill tubes and capsule support structures in LID capsules, decreasing debris and other isolated defects on LDD capsules, and reducing or removing the laser entrance window in MagLIF assemblies. For all approaches, it is critical to have detailed metrology of the as-shot targets to enable clear cause and effect between the initial conditions and the measured mix at stagnation.

Beyond improvements in experimental methods, diagnostics, and targets, it is critical to improve simulations of the mix process and the associated diagnostic signatures. This includes validation of the models that simulate the hydrodynamics behind mix as well as models of the radiative processes. In particular, connecting simulations with experiments requires understanding how mix manifests itself in terms of diagnostic observables. These observables can depend on the multi-dimensional nature of the implosion (i.e. fill-tube induced jets) so it is important to have the capability to post-process 3-D simulations with the response functions of the diagnostics available on the various facilities.

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Common Challenge 3: Identify experimental signatures for each degradation mechanism from simulations and validate against experiments

Background

State of the art simulations are performed to design experiments for each of the three approaches to ICF. These simulations have consistently over-predicted performance. Many different mechanisms, hypothesized from simulations, have been proposed for the reduced stagnation performance relative to simulations in all three approaches. These include low-mode asymmetry [1-3], engineering features and/or other target defects [4-6], intolerable levels of mix into the hot spot [7] and the growth of single-beam nonuniformity for LDD [8]. Direct experimental evidence of a specific mechanism degrading target performance is limited. In addition, as codes and models improve, certain mechanisms that were once believed to be unimportant can later be seen as problematic (e.g. the capsule "tent" for LID).

In addition, each approach has specific issues that have been difficult to simulate. Hohlraum simulations for LID have difficulty with LPI for high gas densities. LPI can be reduced by lowering the gas pressure within the hohlraum, but then kinetic effects and wall motion become important. CBET strongly affects the laser energy delivered to a LDD capsule. CBET mitigation techniques have been studied experimentally but improved target performance has yet to be demonstrated. MDD is sensitive to the laser preheat process, which has been difficult to simulate with the unsmooth Z Beamlet laser beam.

Until recently, most efforts have been focused on understanding implosions at relatively high convergence ratios (where simulations predict that many effects could interact and compromise performance). Under these conditions it is challenging to identify directly from experiments the important sources of degradation. It is recommended that a well-understood, low convergence, and verified "touchstone" implosion or "basecamp" be identified experimentally. This would provide critical benchmarking data for our simulation codes. In addition, derivatives about this basecamp are critical to identify the sensitivities of the various degradation mechanisms. The basecamp implosion would provide a platform for mitigation efforts and inform target design through the analysis of the trade-offs in the various degradation mechanisms. While some implosions have been designed to resemble this in LID [high foot campaign] and LDD, it is not clear whether either of the two approaches currently has a well-understood, touchstone implosion in which degradation mechanisms can be systematically studied and the effects of which can be independently observed.

Plan to address

Experiments are required to identify the basecamp for each approach. These would be low-convergence and perhaps very low velocity implosions where observables show characteristics of "1D" or spherically/cylindrically symmetric behavior. For example, the trajectory of the average hot spot radius (defined in LID/LDD as the 17% contour of the hot spot peak emission), converges with time and then diverges as the core disassembles. The trajectory increasingly deviates from this behavior as nonuniformity is increased in the simulation. Ideally, a basecamp should involve such observables that clearly indicate the '1D-ness' of an implosion. While direct comparison with synthetic observables from spherically/cylindrically symmetric implosions should also be performed, the 1D nature of an implosion should ideally be assessed independent of simulation.

Simulations should be used to identify trends away from this basecamp for varying implosion parameters such as adiabat, implosion velocity, and non-uniformity. Experiments that vary these parameters in a manner prescribed by simulation, will help identify the role of each degradation source semi-empirically. To design these experiments, an extensive list of all possible implosion/stagnation degradation mechanisms should be identified. As degradation sources interact in a non-linear manner, this list should also include potential mechanisms that are believed to be unimportant on their own. A simulation campaign should be carried out for each degradation mechanism, starting with those simulated to have the strongest impacts. The simulations should evaluate experimental signatures of the mechanisms, paying particular attention to their effects on synthetic diagnostics. We recommend coming up with a set of standard synthetic diagnostic routines to be used by the three approaches. Trends should also be carefully evaluated by artificially enhancing or suppressing magnitudes of the degradation mechanisms. The results of the simulations campaigns should be carefully described and compiled based upon anticipated experimental observables.

Many, but not all, degradation mechanisms can be studied with existing rad-hydro codes. However, we anticipate that a number of mechanisms will require robust, routine 3D simulations. Thus, algorithmic improvements of the existing codes should be ongoing to facilitate routine 3D simulations of implosions.

Recommended actions

In order to enhance collaboration across the three approaches and address the common challenges, the workshop panel identified 6 recommended actions that could be taken in the near term. This section describes each of these recommended actions and why they are important.

1. **Clarify the meaning of and observables for pressure and confinement time.** The stagnation pressure (P), temperature (T) and confinement time (τ) are essential for determining the Lawson Criterion, an important metric for ignition, in which Pτ must exceed a critical value that depends upon T. Both high T and P, which is the product of T and density (n), are required for the alpha heating to overcome the radiative and conduction losses of the hot spot. τ must also be long enough for the alpha heating generated during that time to exceed the initial internal energy (3 PV /2) stored in the hot-spot assembly. Presently, T and τ at stagnation are determined from the measured time-integrated neutron spectral broadening, and the intensity and time duration of the emitted fusion gamma rays and/or high-energy x-ray emission, respectively. The burn volume (V) is determined from imaging of the emitted neutrons and/or x-rays. These quantities are then used to infer n and P to match the total yield. The national community should work together to determine what systematic errors may be introduced in the Pt determination using these diagnostic observables and what other measurements could be used to constrain this quantity in all three ICF approaches.

2. **Form a working group on mix analysis and electron temperature.** There are many commonalities across the three approaches in the experimental methods, diagnostics, and analysis tools used to understand mix and measure the electron temperature in the hot stagnation plasma. A national mix working group would enable frequent communication and cross-fertilization in techniques to acquire and interpret the spectral signatures related to the electron temperature and mix. A near term action for this working group would be to collaborate on the development of a high energy continuum diagnostic to quantify the radiated power and time-dependent electron temperature. As a part of this effort, this group should also use simulations to set requirements on the tolerable mix levels for each approach and to identify diagnostic signatures to quantify the mix and its impact on the stagnation conditions.

3. **Form an image analysis working group to share techniques and identify synergies.**

4. **Identify and test peer-reviewed basecamps for each approach.** A target design that simulations predict is least sensitive to various mechanisms that can potentially degrade target performance (long and short wavelength nonuniformities, mix, ice roughness, target offset etc.) should be identified. The performance of this design should be experimentally verified. The goal should be to understand and

predict trends from this "basecamp" when parameters such as nonuniformity, adiabat, implosion velocity are changed. Meetings with the goal of reviewing results from the three approaches ("peer-review") are recommended.

5. **Catalog failure modes and associated signatures.** It is recommended that the effect of each source of degradation on observables be identified. This requires post processing of simulations that systematically include each source of degradation to identify observables. The goal should be to predict trends in observables as each source of degradation is amplified in the simulation. It is expected that the results obtained in any one approach should be transferrable to other approaches. These results should be applied to the existing database of implosions. Systematic experiments over a range of inputs for parameters about the basecamp design should also be compared to the observed signatures to better understand degradation mechanisms.

6. **Develop common simulated diagnostics to connect simulations to experiments.** In all the ICF approaches, it is critical to have validated models that accurately capture trends in the target performance across a range of inputs so that one can confidently extrapolate to the driver and target requirements for ignition and high yield. Validating models against experimental data is not straightforward. Diagnostics often have complicated response functions that depend on the type and energy of the measured particles and result in a complex integral over some subset of space and time. One can therefore be fooled by comparing a simulated plasma quantity (such as electron temperature) to that extracted directly from the diagnostic data without taking careful account of the specific diagnostic sensitivities. In many cases it is therefore most useful to validate models against experiments by post-processing the simulations with a well-known instrument response function and checking for consistencies and differences between the synthetic and measured data. The community should identify the key model-to-data comparisons that would benefit from this approach, define clear requirements on the knowledge of the instrument response functions for the relevant diagnostics, and develop a common approach to creating the synthetic data.

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Addressing Common Challenges in Intrinsic and Transport Properties

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Summary

A key 2020 ICF program goal is to achieve credible physics scaling to multi-mega-joule fusion yields. To achieve this goal we need to develop benchmarked models that we can use with confidence. The Intrinsic and Transport Properties PRD contains the fundamental material and transport properties needed to model and understand ICF and HED experiments. Progress on the development of such models will be most rapid and reliable in a scientific environment that:

- Values and builds on simple, focused, and enduring foundations
- Is open and collaborative and communicates precisely best practices and lessons learned
- Recognizes that many intrinsic properties are interrelated

The working group identified six challenges as being relevant for all three approaches.

Common Challenges in Intrinsic and Transport Properties

- Opacity, emissivity, and radiation hydrodynamics.
- Equation of state: Fundamental questions persist from Thomas-Fermi to highly ionized plasma regimes.
- Hot-spot energy balance: Measurements provide essential constraints on transport physics and performance scaling.
- Stopping power: Understanding DT-α stopping is essential for modeling hot spots, burning plasmas, and credible scaling.
- Thermal conduction: An underinvestigated key energy loss process
- Kinetics: Nonequilibrium effects impacting highly-dynamic plasmas

To enhance collaboration across the three approaches and address these common challenges, we recommend several actions to be taken in the near term. To develop confidence in our models and maintain a community of experts we need to develop and sustain multiplatform, multi-laboratory, focused experiments that produce controlled results. Establishing a mechanism to communicate best practices is considered a high priority.

Recommended Actions

- Develop and sustain multiplatform, multi-laboratory, focused experiments that produce controlled high-precision results
- Develop an atomic physicist pipeline with experts in multi-photon processes and strong radiation fields
- Promote cross collaborations with astrophysics, condensed matter, quantum chemistry, and geophysics communities
- Start a series of EOS workshops to bring together EOS experts for model comparisons and experiment benchmarks
- Develop a mechanism to define and communicate best practices for intrinsic models
- Encourage open and precise documentation when reporting results

Background

The Intrinsic and Transport Properties PRD reflects the quantities and look-up tables for the intrinsic material and radiation transport properties through relevant media that are used by simulations to model ICF and HED experiments. As such there is a great deal of commonality in this PRD across the three approaches, since the approaches encompass similar regions of parameter space using similar materials.

The development of improved models and benchmarking them by controlled experiments is the backbone of this PRD. Resolving discrepancies between models and the comparison with experiment through frequent workshops is a key component to establishing credible scaling models. The opacity community has seen remarkable convergence in models since adopting this approach; the transport and EOS communities should develop similar workshops. It is important that best practices be readily communicated from the experts to the ICF community. Currently this is done in an *ad hoc* manner. Establishing a mechanism to communicate best practices should be a high priority. Equally, precise documentation of the models used in published work is to be encouraged.

Common challenges

The working group identified six challenges as being relevant for all three approaches, amenable to attack over the next several years, and requiring the coordinated efforts of the national program. The group identified a further two less-developed challenges, but for which plans have not yet been developed.

While there is commonality across approaches for intrinsic properties we should also note that intrinsic properties are themselves interrelated. For example, electrical and thermal conductivity are related through the Onsager relations, and so experimental platforms developed for one property could be used for other properties. There are opportunities for refined sensitivity studies that scale multiple properties by a common parameter.

Common Challenge 1: Opacity, emissivity, and radiation hydrodynamics

Background

Understanding radiation transport is essential for modeling ICF implosions. While atomic physics is a well-established discipline that has been highly successful in modeling the properties of isolated atoms, there are still many approximations that are made in opacity codes that have not been validated experimentally. Of special concern are recent opacity experiments performed on the Sandia Z facility by Bailey et al. [1] that show discrepancies as large as a factor of two between theory and experiment, as seen in Figure 3.

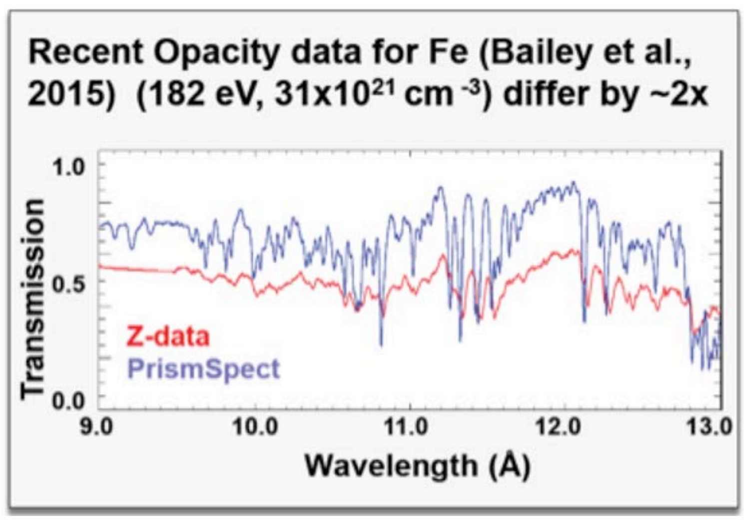

Figure 3. Recent opacity data [1] show serious discrepancies, not only in the overall opacity level, but also in the detailed structure of the lines.

The disagreement shown in Figure 3 is especially puzzling because there is a fair consensus among the local thermodynamic equilibrium (LTE) opacity codes. For the last several decades the authors of the various opacity codes have held regular code comparison meetings, and as a result the outputs of the codes have tended to converge as the state of the art has advanced, even in the absence of experimental data. There are more discrepancies in the outputs of the non-LTE opacity codes, perhaps because there have not been as many cross code comparisons, but also because the underlying radiation-coupled atomic level kinetics is far more complex and numerically challenging than the relatively simple and straightforward statistical equilibrium that applies to LTE.

At a recent opacity workshop some of the main outstanding issues were identified in opacity modeling included charge state distributions, energy level structure, energy level populations, multiply excited states, auto-ionizing levels, photoionization, line shapes, and continuum lowering. Experimental data are necessary to validate the approximations made to model these physical quantities. Experiments could also identify missing physics in the opacity models. Another fundamental issue is making LTE and non-LTE calculations consistent with each other and doing these calculations fast enough that they can be used in the simulation codes.

Progress in numerical simulation methods capable of non-LTE radiation transport in full consistency with the atomic level kinetics and the ambient radiation must progress along with experimental efforts, keeping in mind the following: the notion of "opacity" as the intrinsic material property that fully describes the interaction of radiation and matter is a notion from the theory of stellar interiors where LTE conditions prevail. In all approaches to ICF, where time-scales are short, where equilibrium assumptions are strained, and where radiation is allowed to escape, emissivity is no longer connected to opacity by the Planck spectral function; it becomes a separate material property that must be calculated separately. Furthermore, the same atomic-level populations that determine plasma radiative properties determine other plasma properties, such as thermal conductivity, pressure, specific heat, etc. These quantities are affected by departures from LTE. Without consistent specific heat and emissivity, for example, the response of a plasma to its own emission cannot be simulated correctly. It has been asserted that respect for this radiative-thermal consistency is potentially as, or more, important to the outcome of ICF simulations than the differences in the details among the many atomic models in use today.

Plan to address

With facilities such as Z, ORION, and the NIF capable of doing opacity measurements at the temperatures and densities relevant to ICF, there is an expectation that there will soon be new experimental data to compare with the opacity codes. As seen in Figure 3, this new data could quite possibly challenge our current understanding. It is imperative that the data in Figure 3 be validated on another facility.

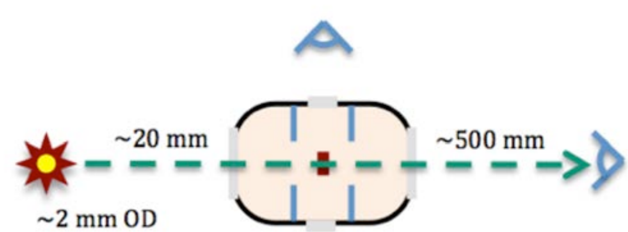

Figure 4. For the NIF opacity experiments the opacity sample will be placed in the center of a baffled hohlraum. X-rays from an imploding backlighter capsule will pass through the sample. The transmission will be measured by a spectrometer on the hohlraum axis. A second spectrometer will look from the side to diagnose the sample conditions.

There is currently an experimental effort to develop a platform for opacity experiments on the NIF, and opacity experiments are also being pursued on the ORION laser. A schematic of the experiments being proposed for the NIF is shown in Figure 4.

These experiments have been planned for a long time. One of the reasons given for the construction of the NIF was the need to do opacity experiments [2]. These experiments have not yet been done on the NIF because of the absence of appropriate high-resolution spectrometers, but these instruments have recently been developed. Initially these spectrometers will make time-integrated measurements. There is still a great need for further work to develop time-resolved spectrometers on the NIF for the opacity experiments. The current experiments are designed to make LTE opacity measurements. Plans are only now beginning for a NIF platform capable of doing non-LTE measurements.

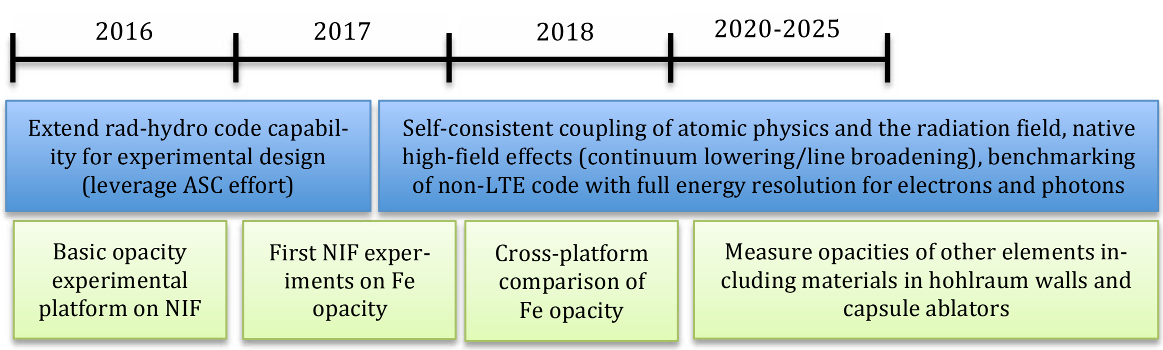

Figure 5. Gantt chart for model developments (blue) and experiments (green) for ICF-relevant opacity data.

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Common Challenge 2: Equation of state: Fundamental questions persist from Thomas-Fermi to highly ionized plasma regimes

Background

Accurate equation-of-state (EOS) of DT fuel [1-5] and ablator/liner materials [6-8] over a wide range of density and temperature conditions is essential for designing and understanding ICF implosions. Fundamentally, an EOS model is required to close the magneto-hydrodynamic equations used in simulations. Accurate EOS tables and models, benchmarked with controlled experiments, will improve our understanding of current integrated experiments, and increase confidence in future designs.

The experimental Hugoniot data cover limited pressure ranges, and there are even less release data. The lack of such data and experimental platforms for off-Hugoniot EOS measurements hinders the precise benchmarking of EOS models, in particular in the warm-dense matter (WDM) regime (during the early part of an ICF implosion) where current EOS models have large discrepancies. Differences of ~10% can have significant consequences for modeling implosions. For example Figure 6, shows the CH Hugoniot pressure and temperature from a first-principles equation-of-state (FPEOS) table compared with the widely used *SESAME*-EOS model. The effect on LDD implosions between these models is also illustrated in Figure 6.

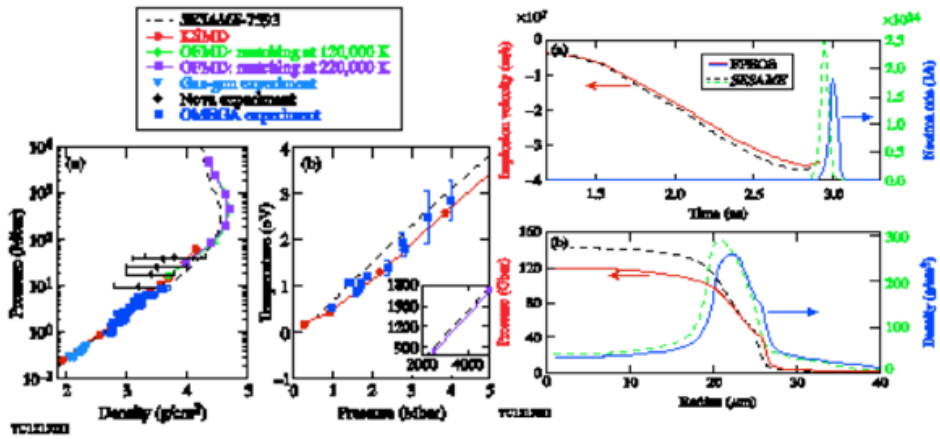

Figure 6. The CH Hugoniot from FPEOS compared with SESAME EOS model and experiments (left two panels); their effects on LDD implosions on OMEGA (right two panels).

There are large gaps in EOS understanding for ICF schemes. For instance, there is no consensus on how to handle the EOS for continuously varying mixtures; the EOS models for foam materials; and how to deal with non-equilibrium and time-dependence. Most importantly, EOS models used in radiation hydro-codes lack self-consistency with other physics models such as opacity and transport properties.

Plan to address

Figure 7 summarizes the four-year plan of work to address the EOS issues discussed above. We recommend an ongoing series of EOS workshops for HED-ICF conditions to bring together EOS experts for model comparisons and experiment benchmarking. These workshops should also include subject matter experts from the opacity and transport communities to improve communication between these communities and ensure self consistency.

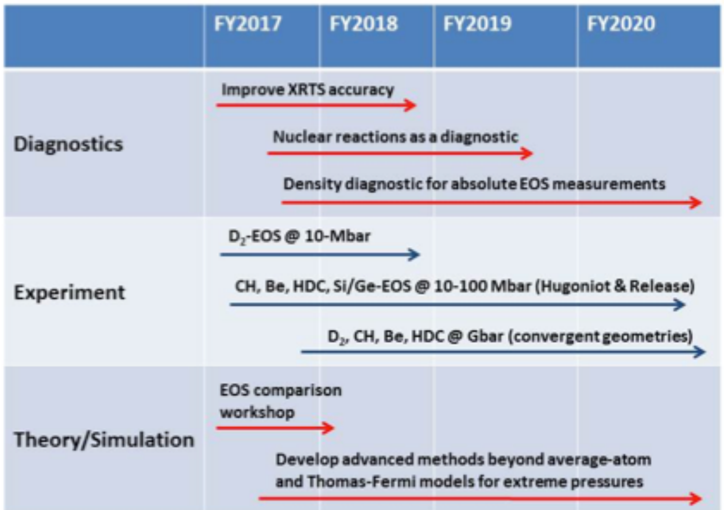

Figure 7. Gantt chart of the proposed EOS research plan.

To benchmark EOS models, controlled experiments across multiple-platforms and multiple-laboratories are recommended. Precise measurements are crucial to develop trustable EOS models. Besides planar geometry, platforms in convergent cylindrical and spherical geometries are required to extend EOS measurements into the Gbar regime. Specifically, EOS measurements for DT fuel in the 10-Mbar regime are needed in the near term; with experiments on DT at Gbar pressures needed to better understand the assembled fuel conditions. For ablator/liner materials, such as CH, Be, HDC, precise EOS measurements at densities of 0.5-10 g/cm^3 and temperatures of 10-100-eV are required. For the LID and LDD approaches, EOS of gold at electron density up to 10^{23}/cm^3 and T=300-eV (LTE) is also required. This would help understand the blow-off gold plasmas in LID-hohlraum and the proposed gold-coating for mitigating laser imprints in LDD.

Advanced first-principles methods such as path-integral Monte-Carlo (PIMC), quantum Monte-Carlo (QMC), and quantum molecular-dynamics (QMD) should be further developed to create more accurate EOS tables for ICF-relevant materials, especially in the WDM regime. For example, better exchange-correlation functionals with appropriate temperature dependence would significantly improve the accuracy of QMD calculations of material properties under extreme conditions. Also, for high-temperature but partially-ionized plasmas there is a need to develop sophisticated methods beyond the average atom model. Based on such *ab initio* results, thermodynamically self-consistent EOS models could then be built for HED-ICF applications.

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Common Challenge 3: Hot-spot energy balance: Measurements provide essential constraints on transport physics and performance scaling

Background

In all three approaches, good performance relies heavily on the overall balance of energy in the hotspot (HS) during the deceleration and stagnation phases. This energy balance is determined by the temperature (T), pressure (P), magnetization, and scale dependence of each of the transport processes. Scaling ICF experiments to higher energy and larger spatial scales will result in changes to the bulk hotspot energy balance, determined by the relative importance of transport processes in a regime where <u>no</u> data exist. The very high T and P required for high yield mean that any attempt to constrain the models contributing to hotspot energy balance must be done in integrated experiments using convergent geometry.

We identified two gaps in our understanding of transport physics under HS stagnation conditions. The first is the sensitivity of the three approaches to uncertainties and/or variations in transport (including conduction, radiation and alpha stopping) physics. As our experiments become increasingly 1D then these sensitivities will become more important. The second is the scaling of hotspot energy balance as we move towards ignition-scale experiments; simple models predict that the various terms in the energy balance contribute differently as the spatial scale of the hotspot is varied (Figure 8), and so it is reasonable to expect that a hydrodynamic scaling of the hotspot will not capture changes in energy balance. An improved description requires that the scaling of our models be constrained by data.

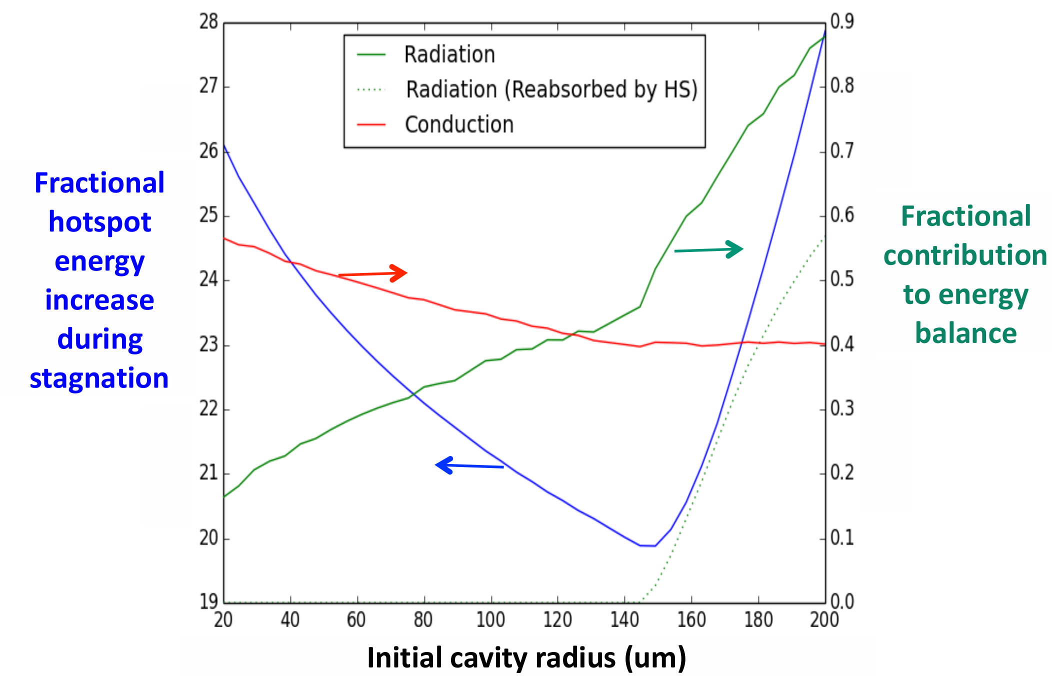

Figure 8. Energy balance calculations of LDD implosions with varying spatial scale, showing a change between conduction and radiation dominated heat flow during stagnation.

Plan to address

We recommend the development of experimental platforms to reliably constrain transport physics models in parameter ranges of importance to stagnation. These experiments should 1) develop reliable methods of diagnosing plasma state variables and hotspot energy balance at the most extreme pressures available; 2) investigate the scaling of terms in energy balance in comparison with hydrodynamic scaling to constrain transport models; and 3) investigate the potential for the manipulation of hotspot energy balance at the current experimental scales and beyond. We envisage experiments in which the overall energy balance is manipulated over a series of shots by changing the spatial scale, initial density, and/or magnetization.

In order to address these challenges we require precise and accurate measurements of the thermodynamic state variables at peak kinetic energy and at stagnation. Progress has been made in this area in recent “GBar” experiments by simultaneously using a set of X-ray and neutron diagnostics. Further development of this approach to include spatially, temporally, and spectrally resolved diagnostics and improved analysis techniques to relate the results to the thermodynamic state is required.

The interpretation of these experiments requires theory and simulations to understand the relationship between the observable quantities and the thermodynamic variables used by transport models. We recommend simulations of the sensitivity of observables to the details of the energy balance in the hotspot. In order to address issues with the large parameter spaces involved, and difficulties with model interpretation, we suggest the development of simplified models that can be sampled rapidly and that have an easy interpretation in terms of energy balance. We recommend a multi-year investigation involving model development and numerical experimental design, alongside experimental campaigns based on scaling the energy balance in existing LDD, MDD, and LID platforms. Researchers should consider scaling according to spatial scale, hotspot mass, magnetization, and other parameters. The suggested timeline is shown in Figure 9. This effort should deliver new diagnostic capabilities to measure the state variables of hotspots, an improved understanding of hotspot energy balance, motivate focused experiments into specific transport physics, and develop applications to manipulate hotspot energy balance.

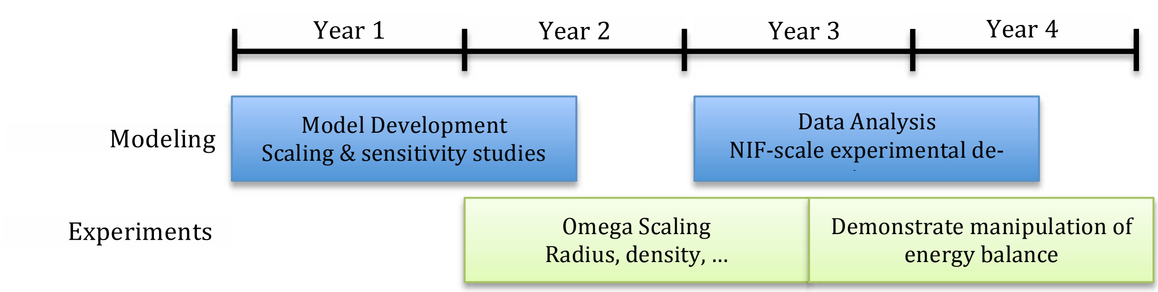

Figure 9. Gantt chart showing model development and scaling experiments.

Common Challenge 4: Stopping power: Understanding DT-α stopping is essential for modeling hot spots, burning plasmas, and credible scaling

Background

The energy deposition by DT fusion alpha particles in the hot spot plasma must be greater than energy loss mechanisms for ignition to occur. Propagating burn and high yield requires understanding alpha transport through the dense fuel. In high temperature plasmas (>20 keV), stopping of alphas on plasma ions also becomes important. Characterizing the alpha stopping in these regimes is necessary for accurate models of ignited and burning plasmas. Sensitivity studies using radiation-hydrodynamic simulations show that knowledge of the alpha stopping power (dE/dx) to ~15% is needed to accurately model current LID implosions [1,2].

Stopping powers must also be known well enough for credible scaling arguments. In subscale implosions in the LID and LDD approaches, alpha ranges are larger than the hot spot size. As the implosion scale is increased, energy deposition from a single alpha particle will also increase, improving the efficacy of the self-heating. The self-heating is roughly optimized when the alpha range is comparable to the hot spot size. Beyond this size, the self-heating efficiency will not increase as rapidly as might be expected from simple scaling.

In contrast, the alpha ranges in burning plasmas for cylindrical MDD always vastly exceed the hot spot radius. Instead, strong axial magnetic fields confine alphas radially and force them to sample the much larger axial fuel dimension, which, by design, typically exceeds the alpha range at stagnation. Significant burn product trapping/stopping has been observed [3], yet a more precise understanding of both magnetic and stopping effects for fusion alphas will determine how high gain MDD designs are optimized for future drivers, where dense cryogenic fuel layers are anticipated [4].

Current experiments studying stopping power in high-energy-density plasmas use two techniques: a separated source of particles and a subject plasma [5], or an integrated experiment, in which an implosion generates both a source of particles and the subject plasma they slow in [6-8]. A limitation of separated source-subject style experiments is that they have not generated plasmas directly relevant to inertial fusion. The primary challenge with integrated stopping experiments is that the measurements are often indirect and less precise, with uncertainties that are difficult to control due to a lack of understanding of the implosion conditions. Based on the current data, a stopping-power calculation accurate to 15% for LID hot-spot conditions cannot be guaranteed. Further, there is limited or no data relevant to burning-plasma scenarios, such as propagating into the dense (and possibly magnetized) fuel, beam instabilities and effects, mixed plasmas, and ion stopping.

Sensitivity studies are also limited to LID implosions at current performances. Sensitivity to stopping-power uncertainties has not been studied for LDD or MDD, for marginally-ignited implosions, or for scaling to larger system sizes.

Plan to address

Because high-precision measurements are needed, to 15% or better, we suggest focusing on the separated source-subject style experiments, as this technique has demonstrated better than the required precision for WDM subject plasmas [5]. This technique is shown in Figure 10. Focused efforts will be needed to extend the subject plasma conditions into more valid regimes, or to match implosion conditions via dimensionless parameters (degeneracy and coupling).

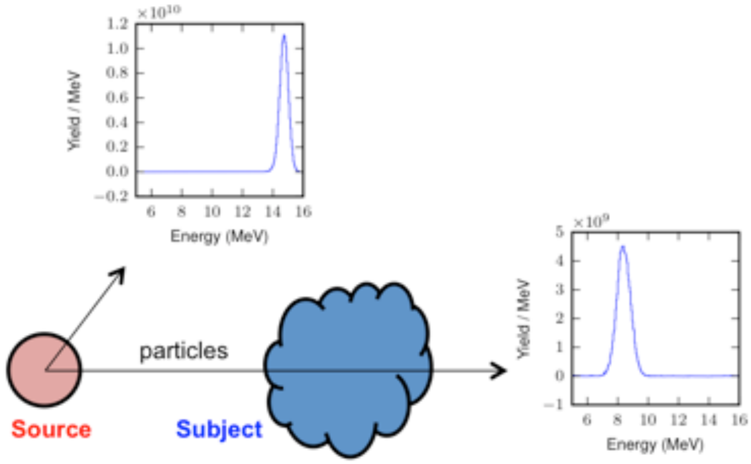

Figure 10. Cartoon of the experimental technique. Particles generated from a source (left) lose energy transiting a subject plasma (right). Both energies are detected to directly measure the stopping power.

Using this platform, experiments should be conducted to constrain the hot-spot stopping power to the required accuracy, study stopping physics relevant to propagating burn, and study mixed plasmas. For propagating burn physics, we are specifically interested in stopping in the dense fuel, and high T_e plasmas where ion stopping becomes important. A rigorous analysis to constrain the stopping power, and its uncertainty, is needed at hot-spot conditions. This analysis should be updated as new data and theory become available, in an iterative process until the 15% desired accuracy is achieved. Better fundamental theory, for example time-dependent density-functional theory, should be applied to the stopping power problem. Additionally, direct theory comparisons should be conducted at relevant conditions. Additional sensitivity studies are needed to evaluate the impact of stopping-power uncertainties on LDD and MDD, and for marginally burning plasmas under all approaches. Finally, an analysis of the impact of uncertainty in the alpha stopping power or range on hydrodynamic scaling estimates for performance at larger scales should be evaluated with simulations or analytic modeling.

The proposed stopping power plan is presented in Figure 11.

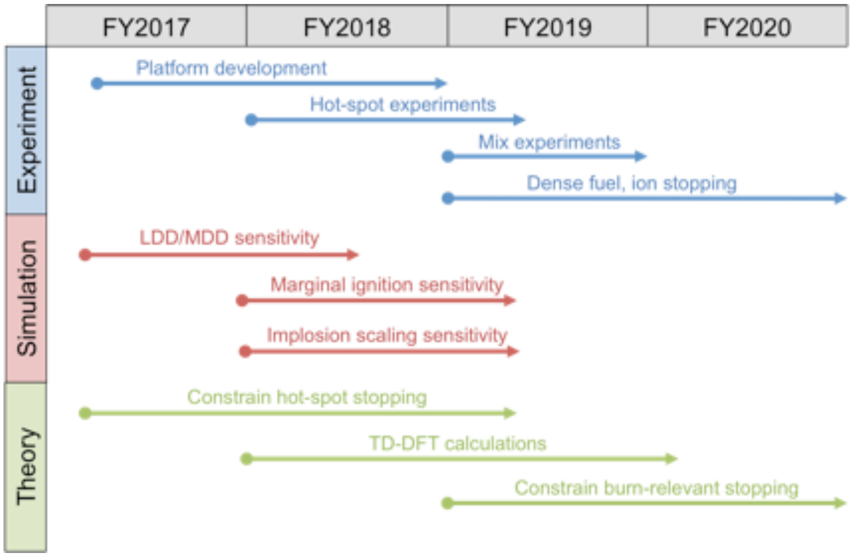

Figure 11. Gantt chart of the proposed stopping-power research plan.

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Common Challenge 5: Thermal conduction: An underinvestigated key energy loss process

Background

Thermal conduction is one of the key loss terms in the energy balance of the hot spot and determines the structure of the ablation front, yet there are <u>no experimental data</u> in relevant regimes. Different thermal conductivity models can vary by more than an order of magnitude [1-3], especially in the warm dense matter (WDM) regime. A lack of focused experiments with well-controlled conditions results in large uncertainties in modeling and optimization of ICF performance for all three approaches.

ICF targets usually contain multiple materials: how to treat thermal transport across interfaces and in mixtures is a grand theoretical challenge. The interplay between thermal conduction and self-generated and/or externally-imposed electromagnetic fields is an experimentally uncharted frontier in ICF. Furthermore, thermal conduction is generally treated as a local diffusive process in hydrodynamic codes; however, the local approximation is easily violated in ICF implosions, and it becomes critical to properly model non-local thermal transport without the artificial flux limiter routinely used. This task is non-trivial even for weakly coupled plasmas, where the models can be benchmarked with fully kinetic Fokker-Planck or PIC simulations, and becomes particularly challenging in the WDM regime, where these methods are no longer applicable. In addition, there is no validated practical method for accurately calculating thermal conductivities of partially ionized plasmas of CH, Be, and HDC at the density range of rho=0.1-1.0 g/cc and temperatures of T=100-1000 eV (LID and LDD), conditions characteristic of the conduction zone.

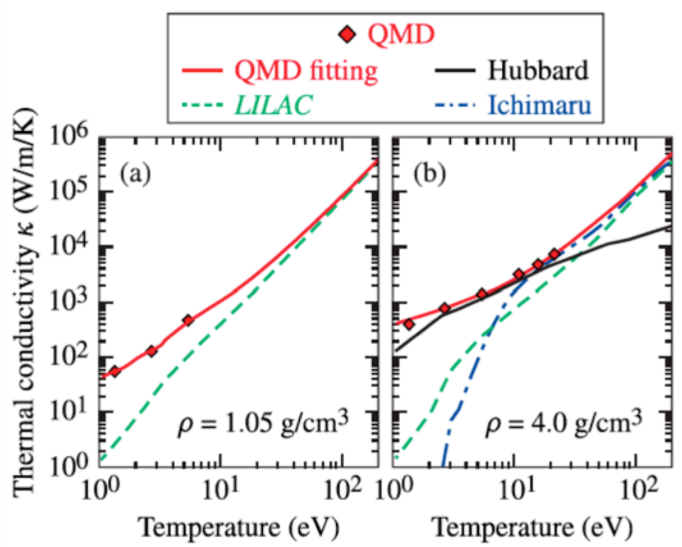

Figure 12. Thermal conductivities of CH vs. temperature calculated by different models [2] showing large divergence between models.

Plan to address

Self-consistency amongst all physics models (EOS, transport and opacity) and between physical regimes when using hydro codes is essential, but often neglected. We recommend an ongoing series of workshops to bring together transport experts for model comparisons and experiment benchmarking, the first of which will be held in Oct. 2016 in Albuquerque, NM.

It is clear that experimental data on thermal conductivity are needed for ICF fuel and shell materials. Given the absence of any published data on thermal conductivity in the HED regime, any data would help for model validation. At present the only experimental platform under development for thermal conductivity measurements in HED regimes is differential heating [4] where a well-defined thermal gradient is induced and time-resolved diagnostics are required to probe the subsequent heat flow as shown in Figure 13. Expanding this concept into multi-facility, multi-laboratory efforts focused on thermal conduction from warm to hot dense matter is necessary to bridge the gap between fundamental properties and integrated effects in ICF campaigns.

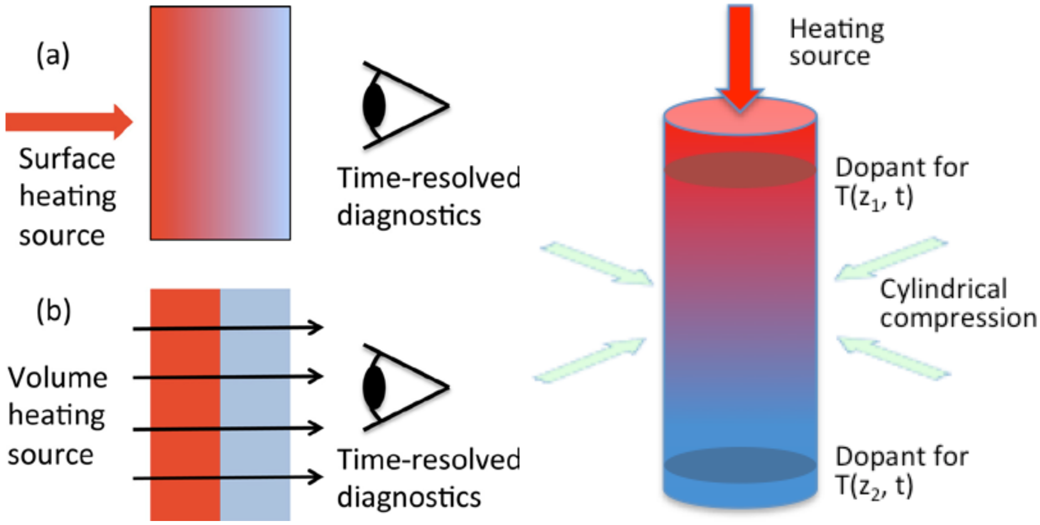

Figure 13. Concept of differential heating fro thermal conductivity measurements. A temperature gradient is induced by (a) surface heating in one material or (b) volume heating in two materials. Time resolved diagnostics probe the timing and amount of the subsequent heat flow [4]. (c) Differential heating in cylindrical geometry. Dopants can be arranged along the axis to generate K-shell emissions as thermometers to map out the heat flow.

The timeline for both experimental and modeling efforts on thermal conductivity is shown in Figure 14. Given the intimate connection between the electrical and thermal conductivity through the Onsager relations, and the inherent difficulties of thermal conductivity measurements, direct measurement of electrical conductivities could also provide essential information for testing the various theoretical frameworks for computing these properties, particularly in the warm dense matter regime.

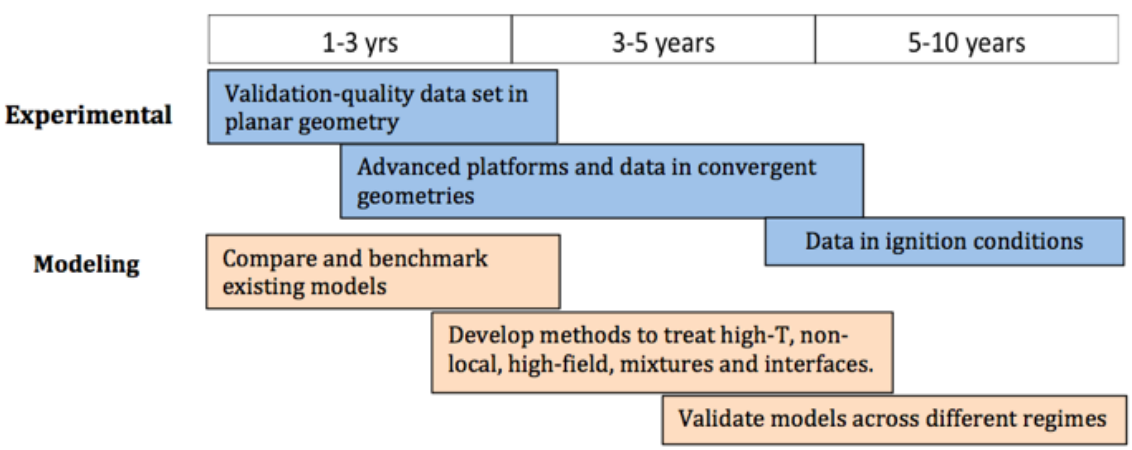

Figure 14. Gantt chart of plan for thermal conductivity work.

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Common Challenge 6: Kinetics: Nonequilibrium effects impacting highly dynamic plasmas

Background

Intrinsic plasma properties (equations of state, transport coefficients and radiative properties) are almost exclusively calculated based on particle and photon energy distributions close to thermodynamic equilibrium. However, this assumption is only valid in the limit of short particle mean-free-paths compared to local scale lengths and time scales greater than local equilibration times. ICF implosions are highly dynamic and produce extreme physical conditions where non-equilibrium distributions occur. A number of intrinsic properties, such as fusion reactivity [1] and electron heat flux, are governed by suprathermal particles that can deviate from Maxwellian even if the bulk of the distribution is close to equilibrium. Furthermore, mean free paths will always exceed the local scale length at material interfaces and shocks.

A recent series of implosions on OMEGA shows that discrepancies between measurements and standard fluid simulations increase with the burn averaged mean-free-path [2]. Observations that demonstrate the importance of kinetic effects in ICF experiments include the need to incorporate non-local thermal transport models to match OMEGA data [3], mix of ion species across initially sharp interfaces in LID, LDD and MDD, often in ways that are not predicted [4], separation of mixtures of fuel ions in OMEGA experiments [5], NIF data where burn-averaged temperature ratios $\langle T\rangle_{DD}/\langle T\rangle_{DT}$ deviate from hydrodynamic predictions [6], and ~2x difference in the phase-transition pressure of Fe when measured on slow (Z machine) and fast (OMEGA) timescales [7].

Fully kinetic simulations based on the Vlasov-Fokker-Planck (VFP) [8] and Particle-In-Cell (PIC) [9] methods are now available and can provide insight into these kinetic processes. However, several kinetic processes remain poorly understood. These include:

- the interplay between perturbed particle distribution functions, electromagnetic fields [10], and intrinsic properties;
- the evolution of heated or shocked interfaces; the effect of collisionless phenomena during the shock phase [11] on hotspot assembly; and,
- how to self-consistently incorporate reduced kinetic models in fluid codes.

The Knudsen number N_K (ratio of the mean free path to a relevant scale length) is widely used as a metric for kinetic effects, however, deviations from 1D geometry, such as asymmetries or interfacial mix, introduce much finer background scales, enhancing the role of kinetic effects [12]; an adequate generalization of the Knudsen number remains to be developed.

Plan to address

Experimental campaigns should be performed to improve our understanding of kinetic plasma processes relevant to all three ICF approaches. In the short term, measurements of plasma shock-front structure [ρ(x), T(x), Z(x), E(x)] on the OMEGA and OMEGA-EP lasers will constrain shock-front modeling in hydrodynamic codes, a critical process for LDD and LID. Suprathermal ions will be studied [13] using fusion reactions with high-energy Gamow peaks, such as ^{3}He-^{3}He. The development of a diffusion experimental platform, based on separated fusion reactants in implosions [4] and/or isochorically heated planar experiments, will allow studies of material interface evolution under various heating and shock conditions. Nuclear diagnostic studies should be extended to evaluate fuel species separation near ignition conditions on the NIF. Neutron and charged-particle spectrometers with improved resolution, and eventually time-resolution (MRSt), should be developed to improve our understanding of the ion distributions in the fusing plasma. Varying the Knudsen number in the initial conditions of the hotspot, for example by varying the initial vapor density using the wetted foam platform [14], will probe the impact of kinetic physics on hotspot formation. A platform to study hotspots with long mean-free-paths in multiple dimensions should be developed using moderate convergence spherical and cylindrical implosions. External magnetic fields could be introduced in these experiments to further constrain modeling of the ion transport.

	Near Term	Mid Term	Long Term
Diagnostics	• Thomson scattering on NIF	• High-resolution neutron and charged-particle spectrometers	• Time-resolved neutron spectrometer [MRSt]
Experiments	• Shock-front structure • Suprathermal ions via high Gamow peak energy	• Diffusion platform • Fuel species separation towards high convergence	• Scaling study of Knudsen number in hotspot • Ion tail depletion platform
Simulation	• Aggregate N_K Post-processor for 2D, 3D fluid simulations • Benchmark reduced kinetic models using kinetic codes	• Detailed kinetic modeling of 1D implosions	• Self-consistent reduced kinetic models in rad-MHD and multi-fluid models
Theory	• Geometrical metrics for Knudsen effects • Impact of E- and B-fields on particle and energy transport and vice versa	• Interplay between kinetic models, EM fields, and intrinsic properties	

Figure 15. Gantt chart for kinetics work.

Analytical and computational efforts on kinetic effects in the short term should include development of an appropriate aggregate metric for ion mean-free-path effects incorporating geometry and asymmetry by post-processing 2D and 3D fluid simulations; fully kinetic simulations to benchmark reduced kinetic models currently in use in hydrodynamic codes; and calculations of intrinsic properties for non-Maxwellian distributions. In the longer term, analytical theory and kinetic simulations should be used to study the impact of E- and B-fields on particle and energy transport for the development of self-consistent reduced kinetic models for use in fluid simulations. If local models prove not to be adequate then non-local extensions, such as multi-group diffusion, should be developed. Detailed kinetic modeling in 1D of entire implosions should be supported to provide a numerical benchmark for kinetic effects in LID, LDD, and MDD. The development of kinetic simulation techniques will provide a valuable area for academic collaborations.

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Additional Challenges

Self-Generated Electromagnetic Fields

In addition to intentionally-imposed fields in MDD, implosions for all three ICF approaches will have self-generated electric and magnetic fields, for example due to pressure gradients and the Biermann Battery effect. Self-generated electric fields [1] up to 1 GV/m and magnetic fields [2] up to 500 T have been observed in laser driven experiments. Magnetic field transport is a complicated issue, where fluid velocity, electron drift velocity, electron heat flow (e.g. Nernst) and diffusion all play a role, which can lead to magnetic field becoming significant far from the regions where it is generated. The program should evaluate the magnitude and effect of these fields for each approach. The primary field diagnostic currently available is proton radiography, which should be applied to ignition scale hohlraums on the NIF (LID) and sub-scale implosions on OMEGA (LDD, MDD). The fundamental physics of the Nernst effect is critical for MDD and may be studied using proton radiography on OMEGA. Further, the scale-dependent physics of these fields should be examined to enable credible scaling to ignition-scale implosions.

Nuclear Physics

Nuclear reactions both generate fusion yield and serve a critical role for diagnosing inertial fusion implosions; therefore accurate cross sections are required. For many cross sections of interest there are no experimental data in relevant energy ranges and standard values (ENDF) rely on interpolations or entirely on theoretical models. Furthermore, fusion cross sections in dense plasmas could be modified by screening effects that have never been measured. The ICF program should evaluate uncertainties in the cross sections that are in use and direct efforts to improve the experimental data and nuclear models on which they are based.

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Appendix: Charge Letter from Dr. Keith R. Lechien

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

NNSA
National Nuclear Security Administration

January 6, 2016

Dr. Donald A. Haynes, Jr.
Deputy Division Leader, XTD
Program Director, Inertial Confinement Fusion
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dear Dr. Haynes:

Please organize and host a workshop on "Addressing Common Technical Challenges in Inertial Confinement Fusion" in Santa Fe, New Mexico, the week of June 20, 2016.

The workshop should emphasize the three most common Principal Research Directions: Implosion; Stagnation and Burn; and Intrinsic Transport Properties. This should include a small select set of invited experts in experimental physics, theoretical physics, design and computational science from each of the following Laboratories: Laboratory for Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and U.S. Naval Research Laboratory (NRL). The deliverable will be a set of white papers and an executive summary identifying major challenges facing laser-driven indirect drive, laser-driven direct drive, and magnetically-driven direct drive, and detailing coordinated, national cross-platform approaches to addressing the most critical challenges common to all approaches. This deliverable will, in turn, be used by National Nuclear Security Administration (NNSA) and the Inertial Confinement Fusion (ICF) Executives to develop and set physics-based milestones as part of the National ICF Program Framework.

I expect that the ICF programs at LLE, LLNL, LANL, SNL, and NRL will make participation in this activity a high priority for those staff members invited to participate.

Sincerely,

Dr. Keith R. LeChien
Director, Office of Inertial Confinement Fusion
NNSA

cc: Bob McCrory, LLE
John Edwards, LLNL
Keith Matzen, SNL
Tom Mehlhorn, NRL
NA-112 ALL

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