Summary and Findings of
The Kinetic Physics in ICF Workshop

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Executive Summary:

It is the finding of this Workshop that the effects of long mean-free-path plasma phenomena and self-generated electromagnetic fields may have a significant impact in ICF targets, based on the assembled experimental data and simulation results to date as presented. We recommend that the NNSA-sponsored ICF Program support a combined simulation and experimental effort to definitively quantify the importance of these effects at ignition-relevant conditions. We propose that the Program pursue a fully-kinetic 1-D test simulation of a radiatively-driven 'high foot' ignition capsule (based on the best-performing NIF implosions), to provide a preliminary verdict as to whether kinetic effects are dynamically important in the ICF ablator and fuel. To achieve this goal we recommend the development and deployment of hybrid particle-in-cell and/or implicit Vlasov Fokker-Planck capabilities, in comparison with perturbative radiation-hydrodynamic tools. Use of these kinetic tools to improve the physical basis of hohlraum models is equally encouraged. A concurrent experimental effort at NIF scale should be considered to isolate and accentuate the integrated role of kinetic and multi-species effects. New proposed experiments include scaling the Knudsen-number and composition of the DT-vapor and DT-ice, and proton radiography of a NIF hohlraum. Continued and expanded experimental and simulation efforts on understanding the "unit physics" aspects of kinetic effects in ICF is strongly encouraged, in particular non-local and non-isotropic particle- and thermal-transport processes driving long-range correlations. We propose to reconvene for a follow-on Workshop in FY '18 to assess progress.

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I. Overview

The Kinetic Physics in ICF Workshop, hosted at Lawrence Livermore National Laboratory on April 5—7, 2016, brought together over 90 researchers from 20 institutions around the world to address the potential impact of kinetic physics on indirect-drive ICF. Thirty-eight talks and topical discussion sessions over three days presented and weighed the evidence for non-fluid phenomena in ICF, summarized the status of analytical and numerical techniques to study these phenomena, and mapped out an experimental and computational path forward to quantitatively assess the role of kinetic phenomena in ICF pertaining to the NIF database.

Systematic anomalies in the NIF implosion dataset were identified in which kinetic physics may play a role, including inferred missing energy in the hohlraum, drive asymmetry, low ρR and high <Ti> compared with mainline simulations, and low ratios of the DD-neutron and DT-neutron yields and <T_i>’s. Several components of ICF implosions were identified that are likely to be influenced or dominated by kinetic physics. Laser-plasma interactions in the LEH and hohlraum interior; the hohlraum wall blowoff, blowoff/gas and blowoff/ablator interfaces; the ablator and ablator/ice interface; and the DT fuel present conditions in which kinetic phenomena could become important. These phenomena include the effects of long mean-free-paths on particle distributions, relative mass- and energy-transport in multi-species mixtures, collisionless phenomena, electric and magnetic fields, and finite-time phase change effects.

Two complementary paths forward were defined to quantitatively address the impact of kinetic physics on ICF: kinetic simulations and experimental scaling studies. High-fidelity physics simulations capturing various levels of kinetic phenomena show promise for application to partial and full ICF simulations over the next three years, including perturbative corrections to hydrodynamics, Vlasov-Fokker-Planck simulations, and Particle-In-Cell simulations. Developing a database of analytical physics tests and experimental data ranging from pure hydrodynamics to purely kinetic physics will support the development, benchmarking, and comparison of these codes, and lead to quantitative kinetic ICF implosion simulations. In parallel, integrated experimental scaling studies will probe the sensitivity of ICF-relevant plasmas to kinetic phenomena: five studies based on existing NIF platforms are proposed, which test sensitivity to kinetic phenomena near the LEH, in the hohlraum, in the DT-vapor and in the hotspot. Together, the three rigorously benchmarked kinetic simulation techniques and the dedicated experimental studies will address the impact of kinetic physics on the prospect for obtaining ICF ignition.

II. Summary of the Workshop

The goals of the workshop were threefold: to assemble and present the evidence for kinetic phenomena in ICF; to summarize the status of analysis and numerical techniques for studying these phenomena; and to map out an experimental and computational plan that enables informed judgment and quantitative assessment on the role of kinetic phenomena in ICF pertaining to the NIF. To address these goals, speakers presented on the current status of their experimental, computational, or theoretical research, and the outcomes of these presentations were discussed in sessions at the end of each day.

a. Physics description

The indirect-drive ICF experimental designs used at the NIF generate a wide range of plasma conditions, ranging in density from $10^{19} – 10^{25}$ particles per cm^3, in temperature from 0.01 – 10 keV, and in material composition from light ions (D,T) to high-*Z* (Au and DU). Consequentially, a broad range of physical phenomena relevant to various parts of the ICF implosion were discussed at the workshop with regard to the possible influence of kinetic physics. For the purposes of this workshop, *kinetic physics* refers to phenomena that occur on the time- or length-scale of particle collisions. For ions, these scales are generally defined by the collision time τ_{ii} and the mean-free-path λ_{ii}, which may be parametrized as follows:

$$\tau_{ij} = \frac{A_i}{\sqrt{A_{red}}Z_i^2 Z_j^2 \ln\Lambda}\left(\frac{n_j}{10^{20}\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T_i}{1\,\mathrm{keV}}\right)^{3/2}[4.65\,\mathrm{ns}]$$

$$\lambda_{ij} = \frac{A_i}{A_{red}Z_i^2 Z_j^2 \ln\Lambda}\left(\frac{n_j}{10^{20}\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T_i}{1\,\mathrm{keV}}\right)^{2}[1.15\,\mathrm{mm}]$$

for ion masses A and charge states Z, reduced mass A_{red}, ion densities n, ion temperatures T_i, and Coulomb logarithm ln Λ. *Kinetic effects* refers to any observed phenomena that result from such physics, causing the evolution of the plasma to differ from single-component hydrodynamic evolution, which assumes collisional scales are much smaller than the temporal and spatial scales of interest.

These definitions lead to two important cautionary ideas when attempting to quantify the impact of kinetic physics in ICF. First, due to the time- and length-scales involved, kinetic physics are difficult to measure directly: either resolution on the order of picoseconds and microns is necessary, or extreme conditions that are unlike ICF plasma conditions are required. Second, even if *kinetic physics* significantly perturbs some aspect of plasma evolution, this does not necessarily imply unique *kinetic effects* are observed. Observed quantities tend to be macroscopic, integrated, and comparatively few in number, such that the effects of various microphysics – kinetic physics, equations of state, turbulence, preheat, and others – intrinsically confound each other as potential explanations. In response to this difficulty, the workshop finds that developing capabilities to reliably predict the macro-scale effects of kinetic mechanisms is critical to confirming or rejecting kinetic physics as significant within ICF. The workshop also supports the

	Phenomenon	**Will affect**	**Likely Impact**	**Ease of Assessment (Expt / Sim)**	**Experimental benchmark [Personnel]**	**Theory/simulation test [Personnel]**
1	LPI: time- & space-dependent hot e-production	Time-dependent implosion symmetry	**High**	**High**	Image surrogate hi-Z cap [Dewald]	Hot e- production & interaction with fuel [Afeyan]; High-resolution PIC [Fiuza]; VFP [Larson]
2	Multicomponent diffusion / multifluid transport and mix	Au blow-off plasma	Medium	Low	Optical Thomson scattering (TS) on OMEGA [LePape]	Multicomponent hydrodynamics with N species [open]
3	"	Ablator	Low	Low	X-ray scattering and diffraction [open]	Multicomp. hydrodynamics [open] PIC with radiation [open] Multi-fluid [Larroche]
4	"	Ablator/DT interface	Medium	Low / **High**	Diffusion at isochorically heated interface [Fernandez]	Shock break-out in multi-fluid [Bellei, Larroche], PIC [open], VFP [Fernandez], MD [Murillo]
5		DT ice/gas interface	Low	Medium	[open]	Shock break-out in multi-fluid [Bellei] VFP [Larroche]
6	"	Fuel separation	Mixed results	Med / **High**	Moderate N_K implosions [Petrasso] [Herrmann] D,Ar implosions [Hsu]	Multicomp. hydro [Hoffman], VFP [Larroche], PIC [Le, Mason]
7	Interpenetration	Ablator/gas/Au collision region	**High**	Med / **High**	TS of interpenetrating flows [LePape]; Dot spectroscopy [Barrios]	Multicomp. Hydro [open]; Multi-fluid [Larroche]; PIC [Kemp, Higginson];
8	Multispecies/multifluid equilibration	Initial conditions of hotspot	Medium	Med / Low	High N_K implosions [Petrasso, Rinderknecht]	PIC implosions with laser drive [open]; VFP [Larroche]
9	Shock structure	Entropy of fuel, hotspot formation	**High**	Medium	Thomson scattering for 1D shocks [Rinderknecht]; Proton radiography for 1D shocks [Ping]; multi-species burn history [Sio]	Multi-comp hydro [Hoffman, Vold, Mason, Atzeni], VFP [Taitano, Larroche], PIC [Bellei, Mason]
10	Knudsen layer effects	Burn, yield, Ti	Medium	Low / **High**	Variable NK in NIF implosions [Olsen]	VFP of fuel [Larroche]; PIC of fuel/implosion [Le, Mason]
11	Magnetic and electric fields in hohlraum and capsule	Transport	**High**	Medium	Proton radiography [Li]	Verify transport physics; Simulations with imposed fields (multi-comp hydro, PIC); study field generation
12	Phase change dynamics	Ablator/DT interface	Unknown	Med / Low	Spallation from planar samples; vary ablator melt conditions	Verify whether ion kinetics requires delayed phase change [Orth]

Table 1: List of kinetic physics phenomena found likely to significantly impact indirect-drive ICF as pertains to the NIF. The likely impact and ease of assessment (using experiments/simulations, respectively), is estimated based on the workshop discussions. Experimental benchmarks and theoretical or simulation tests are proposed for each item; associated personnel are listed.

development of high-resolution diagnostics on the NIF, as these will assist in breaking the degeneracy between physical explanations.

The phenomena found most likely to significantly impact ICF experiments are summarized in **Table 1**, including for each the estimated importance, ease of assessment, and proposed experimental, theoretical and simulation studies. These phenomena will be described in greater detail in the following sections.

b. Experimental evidence of kinetic physics in ICF

The workshop identified four main regions in the ICF design where kinetic phenomena are expected to play a role, either from theoretical considerations or experimental evidence: laser/plasma interactions during the laser drive, the hohlraum wall/gas and wall/ablator interface, the ablator and DT ice layer during the shock phase, and the core of the fuel during the shock-phase and hotspot assembly. The experimental evidence for each of these categories is described below. Anomalies in the NIF dataset related to several of these categories were also identified, and are described with discussion of potential causes.

i. Laser/Plasma Interaction

Interactions between the laser and the underdense plasma in the hohlraum produce electron kinetic effects in the form of persistent non-equilibrated electron distributions, driving instabilities such as 2-plasmon decay, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). Non-local thermal equilibrium (NLTE) and cross-beam energy transport (CBET or XBET) models attempt to address the effect of these distributions on energy transport in the hohlraum. These laser-plasma interactions have been extensively studied both theoretically and empirically. However, the detailed time- and space-dependent production and transport of suprathermal ("hot") electrons from these processes in the NIF hohlraum, and their impact on implosion symmetry and the velocity distribution function in the hotspot as a function of time, is not well understood [Afeyan]. Experiments on NIF have imaged the 2D distribution of hot-electron preheat of the capsule during the picket, demonstrating strong electron beaming in hohlraums with 0.6 mg/cc ^{4}He gas-fill density [1].

Experiments have shown the electron 2-stream instability produced by thermal gradients in an ablated plasma enhances laser absorption and inhibits heat flux, with possible impact on hohlraum performance [2].

ii. Hohlraum

Experiments on the NIF present several anomalies related to hohlraum performance. The need for time-dependent "Oggie" multipliers on the laser power to match the measured hohlraum x-ray flux and implosion performance remains both significant (representing a loss of ~10—30% of laser power for gas-filled hohlraums) and unexplained [3]. In near-vacuum hohlraums (NVH) the efficiency of laser coupling is better predicted than in gas-filled hohlraums [4]; however, the observed low-mode drive asymmetry is difficult to simulate: experiments are generally more prolate than predicted [5]. Several kinetic mechanisms have been proposed in this regime.

Interaction of the wall blowoff plasma with the fill-gas and ablator blowoff produces conditions in which counterstreaming plasma distributions generate a mix layer. The formation and evolution of this interpenetration layer has been proposed as a cause for the symmetry discrepancy between NVH experiments and simulations [5], as the lack of interpenetration in the code causes a density spike at the interface, which blocks inner-beam propagation. Particle-in-cell (PIC) simulations demonstrate reduced and smoothed electron density as well as the elimination of temperature spikes in the interaction region, as compared to hydrodynamic simulations [Kemp]. Recent surrogate experiments on OMEGA have demonstrated measurements of density, temperature and flow-velocity evolution near interpenetrating C-Au as well as C-C and C-Al layers [LePape]. These techniques will be valuable for detailed study of multi-species plasma evolution.

Strong electromagnetic field structures have been observed in the hohlraum using proton radiography [Li]. Electric fields are self-consistently produced by electron pressure gradients, which are prevalent at plasma interfaces. Electric fields associated with the Au wall/gas diffusion layer were observed on OMEGA experiments approaching ~1 GV/m [6]. Magnetic fields are generated in the hohlraum by unaligned density and temperature gradients via the Biermann battery mechanism, and have been observed at laser-plasma bubbles and near the LEH on the order of 0.1—1 MG [7]. Although the magnetic pressure is insignificant (~0.01 MBar) compared to the hydrodynamic pressures in the experiment, the impact on energy transport and other intrinsic plasma properties could be significant.

The possibility of significant hydrodynamic instability growth at the wall/gas interface is suggested by the appearance of scalloped features in self-emission images from the LEH. While not a kinetic effect for the purposes of this discussion, such instabilities would exacerbate the impact of the kinetic physics by reducing the scale of gradient-driven features and introducing turbulent flow.

iii. Ablator and DT ice layer

Separation of ion species has been directly observed in ablated plasma from a CH target by optical Thomson scattering: the ion species fraction far from the ablation front was observed to evolve from 90% H to 67% H (the initial target composition) over 9 ns [8]. This effect is not expected to directly impact ablation drive; however, the surrounding hohlraum environment is affected in a time-dependent manner [Ross].

The ablator/ice boundary is a classical sharp interface before modification by preheat and shocks, implying mean-free-path scale physics will be relevant there. PIC simulations indicate that diffusive mixing ($\Delta x \sim t^{1/2}$) accurately represents the behavior of the ~0.1x peak density contour, but lower-density mix contours propagate “superdiffusively” ($\Delta x \sim t^{1/2} - t^{1}$). Preliminary radiographs of an isochorically heated gold-HDC interface on the Titan laser appear to confirm such superdiffusive transport [Fernandez].

iv. Shocked fuel and hotspot assembly

Several persistent anomalies related to the hotspot and fuel assembly on the NIF were presented. In comparison of experimental data to 2D postshot simulations, the measured DT neutron down-scatter ratio or DSR, which is proportional to fuel areal density, tended to be 10—20% lower than predicted, whereas the experimental Brysk temperature inferred from the DT-neutron spectral width was 20—40% higher than predicted. The ratio of the Brysk temperatures inferred from DT-n and DD-n appears too large to explain by burn-weighting due to reactivity or unstagnated flow velocity [9]. A larger-than-predicted ratio of DD-n to DT-n yields (up to 40%) is observed on many cryogenically layered experiments [Patel]. Several 3D simulations have been performed and show similar trends. Artificially reducing thermal conduction in the DT fuel by 0.5x produces better agreement with the measured ρR and $\langle T_i \rangle$ values, demonstrating that microphysics can produce the observed anomalous effects [Clark]; however, it is not clear that conductivity, rather than other microphysics or unconsidered physics, is the correct explanation for the data.

In the fuel the Knudsen number, defined as the ratio of ion mean-free-path to a characteristic plasma scale length (often the radius of the fuel at nuclear burn: $N_K = \lambda_{ii}/R$) provides a convenient dimensionless parameter for the dominance of kinetic physics. Directly-driven implosions on OMEGA and the NIF have demonstrated reduced nuclear yield and burn-averaged temperatures relative to hydrodynamic simulations for plasmas with $N_K > 0.01$ [10] [Rosenberg]. The reduced reactivity due to loss of tail ions and ion diffusion appear to be the primary causes of this yield reduction [11].

Ion species separation, an effect of ion mass diffusion in multi-species plasmas, has been extensively studied as a likely explanation for multi-species yield anomalies observed on OMEGA. Several studies have reported reduced yield relative to a simulation or analytical model in multi-species fuel mixtures [12—15]. The diffusive species separation hypothesis was tested by comparing implosions with DT fuel to hydrodynamically-equivalent implosions with DT+^{3}He and DT+H: the predicted reduction of DT yield for the former case and enhancement of yield in the latter case was observed [Herrmann]. Nuclear measurements from implosions with initially 50:50 D^{3}He fill and $N_K \sim 0.5$ were used to infer an increase of the ^{3}He concentration in the core to 70±10% by peak nuclear emission [16]. A comparison of DT-neutron yield to DD and TT yields on implosions from OMEGA and the NIF appears to show anomalously high (TT/DT) or low (DD/DT) simulated yield ratios for $N_K > 0.01$ but accurately simulated ratios for $N_K < 0.01$ [Casey].

New techniques for studying the effects of ion diffusion were presented. Species separation was directly probed in mixtures of deuterium with trace amounts of Ar by time-resolved imaging of the Ar spectral lines, showing a concentration of the Ar in the core [17] [Hsu]. A separated-reactants platform, in which deuterated plastic shells filled with HT gas were imploded and the DT-gamma and HT-gammas were measured to investigate time-dependent gas/shell mix, has been demonstrated and will be used to validate theories on mix evolution [Schmitt].

The propagation of strong shocks through the DT fuel and vapor was highlighted, as the structure of shocks is intrinsically shaped by kinetic physics. One observable result is the formation of electric fields at shock fronts, which has been demonstrated in theory and in PIC simulations [18]. Strong, persistent electric fields have been observed at spherically converging shock fronts [19]. Experiments have successfully imaged the electric field structure at shock fronts produced on the OMEGA-EP laser using proton radiography [Hua]. High-precision (~10ps) relative measurements of the emission history of x-rays and multiple nuclear reactions from implosions have been demonstrated using a scintillator-based system on OMEGA [Sio]. These new capabilities will support detailed benchmarking of kinetic physics models of shock propagation in planar and spherical geometries.

The low DT-vapor density (0.3 mg/cc) in the core of an ICF implosion is strongly shocked prior to the deceleration phase, producing plasma with Knudsen number in the range 0.2—0.8 where kinetic physics is likely to dominate. Implosions probing the behavior of similar strongly-shocked D^3He plasmas on OMEGA demonstrated thermal decoupling of the ion species during the shock-rebound phase [16]. This behavior implies the DT-vapor undergoes a period with non-thermalized distributions prior to the deceleration phase, which will modify the internal initial conditions for fuel compression and hotspot formation [Rinderknecht].

c. Current capability of kinetic physics simulations

Results and techniques of several approaches to simulating kinetic physics were presented. The kinetic physics models described cover a range of fidelity, with corresponding trade-offs in computational resources. An important consideration when comparing the relative benefits of these techniques is that it is not obvious at what level of fidelity the effects of kinetic physics on the macroscopic behavior of the plasma are sufficiently well modeled. The following description of the present status of these techniques includes several examples in which simulations with different levels of fidelity predict different outcomes. As these techniques continue to develop, systematic comparison between the simulations, theory, and experimental benchmarking will be necessary.

i. Modifications to hydrodynamics

Modifications to single-species hydrodynamics simulations allow the inclusion of perturbative models of collisional physics, which were shown to have significant impacts on ICF-relevant test cases. Such models have been referred to as “reduced ion kinetic” models [11]. Models of ion heat conduction and real plasma viscosity are available in single-fluid codes. Including a viscosity model modifies the structure of shock fronts and generally smoothes strong pressure gradients, with significant impact on converging-shock problems [Vold, Mason]. While integrated observables such as the yield and spectrally-inferred burn-averaged temperature are not necessarily changed significantly by including a viscosity model, the profile of nuclear production was shown to change dramatically [Atzeni]. Self-consistent electric and magnetic fields can be included using the MHD equations, and couple in non-obvious ways with heat conduction, viscosity, and other extensions: magnetic fields in the core of an implosion were twice as large when plasma viscosity was included [20] [Mason]. The "loss" of the most energetic ions in a thermal plasma of finite size due to their relatively long mean-free-paths reduces the fusion reactivity [21]; this effect has been included in models [Zimmerman] and accounts for approximately half of the observed reduction in yield with Knudsen number [11].

Although single-fluid hydrodynamics solves only a single "average-ion" equation for momentum and energy transport, the relative mass diffusion and heat transport of different ion species can be included using perturbative methods: these approaches are referred to as "multi-component hydrodynamics." Generally speaking, the rigorous extension of single-species kinetic models such as ion heat conduction and ion viscosity to multiple species requires summing over separate pairwise calculations for each species, which remains to be done [Zimmerman]. To date, binary diffusion has been implemented in several codes; these implementations have been validated but are only strictly valid for two species. Valid treatments for arbitrary numbers of ion species have been developed [Cabot] [Simakov] [Kagan]. Models implementing these physics for N species requires of order N^2 calculations per timestep. Single-species codes generally include a separate energy equation for electrons, as the large mass difference between the species allows the electron and ion temperatures to differ significantly. Inclusion of separate energy equations for each ion species is possible, requiring updates to equations of state, fusion reactivity, coupling, heat conduction, and others.

Multi-component tools have been successfully applied for modeling experiments. The yield and $\langle T_i \rangle$ anomalies observed with changes in Knudsen number and ion species fraction in shock-driven implosions on OMEGA are reproduced by models including Knudsen-layer reactivity reduction and ion diffusion, although the profile of nuclear production is not accurately captured [22]. Although shock front structure is not expected to be well modeled by hydrodynamic codes, multi-component simulations of a shock front in a planar multi-species (H, Ne) plasma was found to agree reasonably well with a prediction of analytical theory [Hoffman]. Simulations including ion diffusion only predict an impact of ion diffusion on the yield of OMEGA gas-filled implosions, but not of NIF SymCaps and "BigFoot" DT-layered implosions [Ho], consistent with some experimental observations [Casey] but inconsistent with Vlasov-Fokker-Planck simulations, as will be discussed below.

Additional fidelity is obtained in hydrodynamic simulations by including separate momentum and energy equations for each ion species. Such "multi-fluid" hydrodynamic simulations have been shown to predict new phenomena. Multi-fluid simulations of shock breakout from a solid-density layer into a gas introduce an "ion bunch" of the solid material streaming ahead of the shock front, which is not observed in multi-component models [18]. Experimental data partially support this result; however, a concrete demonstration has not been performed [Bellei].

ii. Kinetic simulation approaches

The particle distribution function is resolved in simulations based on the Vlasov-Fokker-Planck (VFP) equation. Such simulations intrinsically capture the physics of multiple ion species as well as collisional effects such as conduction, viscosity and diffusion, by directly evaluating the advection-diffusion in velocity space due to the Coulomb collision operator. The need to resolve collisional timescales makes full implosion simulations and high-Z materials difficult. Using hydrodynamic simulations to provide boundary conditions for VFP simulations has allowed studies of D^3He-gas filled implosions on OMEGA and DT-layered implosions on NIF using the FPion code [Larroche]. Simulations of D^3He-gas filled, shock-driven implosions accurately reproduce the experimental results for moderate-N_K implosions, demonstrating both separation and differential heating of the ion species [23]. However FPion does not appear to reproduce the observed yield anomaly in compressively driven D^3He-gas implosions, possibly due to unmodeled fuel/shell interface dynamics [24]. FPion simulations of sub-igniting NIF implosions show significant perturbations in the D:T ratio and differences in the D and T temperature of the hotspot up to peak compression [25], while simulations of igniting NIF implosions show earlier ignition at lower fuel densities [26]. The discrepancy between this result and the multi-component simulations described earlier highlights the need for work on various levels of fidelity and comparison between these approaches. Recent developments in the iFP code, including adaptive meshes, exact discrete energy and momentum conservation, and fully implicit time stepping, enable simulations to approach the scale of full experiments [Chacon]. This code is undergoing extensive verification against analytical test problems [Taitano].

Particle-in-cell (PIC) simulations resolve particle distributions through Monte Carlo simulations of particle collisions. This approach intrinsically captures multi-species and collisional physics, and also intrinsically models particle interactions with electromagnetic fields. Direct PIC simulations have validated the Ji-Held model of thermal conductivity in the presence of a magnetic field [27] and have confirmed heat-flux inhibition during laser ablation [Sunahara]. The hybrid-PIC approach, used in codes such as LSP [Thoma] and ePLAS [28] [Mason], allows kinetic or fluid simulation of electrons and multiple ion species including interactions with electromagnetic fields. Initialization of LSP from hydrodynamic simulations has been used to study implosions on OMEGA, demonstrating ion species separation in DT fuels and improved modeling of nuclear production history [Le]. Monte Carlo fusion calculations were shown to provide a good understanding of nuclear data recorded from a collisionless, counterstreaming plasma [Higginson]. Implementation of a laser ray-tracing capability in LSP is ongoing and will allow simulations of implosions directly within the code [Thoma].

Molecular Dynamics (MD) simulations resolve arbitrary levels of Coulomb coupling, including the full inter-atomic potentials produced by all ions and electrons present in the problem. The MOD-MD code uses multiple scales to accurately account for both bound and unbound electrons. At this level of fidelity, only small scales may be simulated directly (~1 micron, ~10 ps). Models of a classical CH/DT interface being heated uniformly show hydrogen penetrating more deeply into the ice layer than carbon [Murillo].

d. Theoretical progress

Theoretical efforts continue to analyze relevant kinetic physics and to define when this physics creates measurable kinetic effects and their impact.

The growth of plasma bubbles from the gold hohlraum wall driven by laser absorption ranges from near-solid density, cold plasmas near the wall to low-density, hot Au interacting with the hohlraum gas and ablator blowoff. The strong thermal gradients and range of ionization states within the Au bubble suggest that mass diffusion of the Au ions could play a strong role in the bubble profile: calculations of the mass diffusion coefficients for two species with equal mass and differing charge states (T, ^{3}He) predict electron-thermal, ion-thermal, and electric potential terms are active, with the thermal and electric terms having opposite sign [29]. The "plasma adiabat lapse rate" predicts an inversion of the temperature profile in this ablated bubble, which is not captured in a hydrodynamic description [30]. The enthalpy of mix and possible turbulent motion in these regions and at the wall/gas interface provide a potential sink for energy in the hohlraum.

In the ablator, the phase change from solid to a plasma state is not instantaneous, passing through a temporary super-heated solid state. In this scenario, the shock- and phase-change-fronts could separate spatially, such that shock breakout ejects or spalls solid chunks of the ablator material into the DT fuel. This effect could be the source of 'meteorites' observed in the x-ray data during the National Ignition Campaign (NIC) [31] [Orth].

In the fuel, the loss of high-energy ions in the Knudsen layer was found to produce a reduction in the observed neutron spectral width for a given plasma temperature, in addition to the previously-identified reduction in reactivity. Importantly, such effects on the scale of the ion mean-free-path are exacerbated by large perturbations to the fuel shape, which are observed in experiments and multi-dimensional simulations: the relevant scale for local kinetic effects is distance to the nearest boundary, which in the case of strong asymmetries or mix is much smaller than the radius of the hot spot [Kagan]. PIC simulations of the Knudsen layer show that fusion observables are impacted by changes to the background energy flow, density and temperature, rather than the ion tail distribution alone [32] [Cohen].

III. Proposed Plan of Action

The workshop discussions produced two main paths forward to quantitatively assess the impact of kinetic physics in ICF: the "code pathway", in which promising high-fidelity simulation techniques are verified and benchmarked leading to simulations of integrated ICF implosions; and the "experimental pathway", in which integrated, systematic scaling studies are defined and performed to test the importance of kinetic physics in ICF-relevant experiments.

a. "Code Pathway": Benchmark advanced codes for fully kinetic ICF simulations

Three main categories of simulations potentially capable of modeling full ICF implosions were identified: multi-component hydrodynamics (abbreviated "Hydro+"), Vlasov-Fokker-Planck (VFP), and Particle-In-Cell (PIC). We propose to systematically verify and benchmark the three promising code techniques (Hydro+, VFP, and PIC) against a database of test problems and fundamental physics experiments, then use each to simulate components of ICF and, ultimately, full ICF implosions.

Much progress has been made in each of these techniques and initial results modeling kinetic experiments have been achieved, as described in Section II. However, careful benchmarking of each technique is required before implementing them for guidance of the ICF effort. It has been noted, for example, that a simulation of a NIF DT-layered implosions using a hydrodynamic + ion diffusion code indicated negligible impact from kinetic physics, whereas a similar simulation using a VFP code indicated significant changes to the hotspot composition and energetics. Careful effort is needed to determine whether this result is valid and resolution of the ion distribution function is necessary to capture all the relevant microphysics for hotspot assembly.

The creation of a database of analytical test problems and "unit physics" experiments will support this work. A list of test problems and experimental datasets that have already been defined are described in **Table 2**. The problems range from pure hydrodynamics (regimes in which all kinetic physics is negligible) to pure kinetic effects (regimes in which kinetic physics dominates). Experiments are drawn from the published results presented at the workshop, including the shock-driven exploding pusher scans in density, yield anomaly studies, shock-tube studies, magnetic- and electric-fields in hohlraums and planar experiments, and more. Attendees of the workshop will define and carry out further studies to extend these datasets and make the results available. The ongoing and proposed experimental, theoretical, and simulation efforts described in Table 1 will contribute to this database as well. New and promising diagnostic techniques and experimental platforms, such as x-ray scattering and diffraction measurements at LCLS, will provide benchmarking data with improved quality and in new regimes [33]. Benchmarking of the codes against these problems and datasets will provide better understanding of the capability and range of validity for each tool, and will feed back into defining the most important improvements to those tools.

The goal of this pathway is the performance of detailed studies of integrated ICF implosions using all three techniques. A summary of the current status and the expected timeline to produce such an integrated study is given in **Table 3**. The Hydro+ model ZPKZ is currently the most developed of the three approaches: as an extension to a single-fluid radiation-hydrodynamic code, much of the physics necessary to simulate an ICF implosion (i.e., laser ray-tracing, multi-group radiation diffusion, benchmarked EOS and opacity tables) is already present. The code is currently undergoing verification of the multi-component models and benchmarking to experimental data [11]. Credible studies of ignition-relevant components and of a full ICF implosion should be possible using this code in the timeframe of 6 to 12 months.

The hybrid-PIC approach spans the range between hydrodynamic and explicit PIC treatments within a single code. LSP currently includes single-group radiation diffusion, and ray-tracing for laser drive is in development [Thoma]. This code has already been applied to study the fuel in spherical implosions by initializing from hydrodynamic simulations [Le] [18]. Verification of the implosion physics in the code against analytical models of spherical implosions and experimental datasets is needed; however, significant development is not required. Simulations of radiation-driven implosions given a radiation source are expected to be feasible within 1—2 years. Simulations of hohlraum-relevant physics using LSP is complicated by the presence of high-Z materials (e.g., Au), which require improved ionization/recombination physics and are computationally intensive due to small collisional timescales. Studies of component physics of the hohlraum are feasible using hybrid-PIC capabilities and will be valuable for benchmarking hydrodynamic models; however, explicit PIC simulations of hohlraums are not anticipated in the near future. The ePLAS code presently includes self-consistent, implicit electric and magnetic fields, laser drive and thermonuclear burn. Ongoing work adding collisions to multi-component PIC ions will enable studies of species separation and kinetic effects in target implosion shocks.

Physics	Test Problem	Experimental Dataset
Hydrodynamics	Shock jump conditions: density jump, density drop, reflecting shock, etc. Spherically-converging shock [34]	NIF Indirect-drive exploding pusher [37]
Multi-component diffusion	Interface mixing (D/Al) [35] Diffusion of "two-color" H, Ne [Zimmerman]	Separated reactants: [38], [Schmitt] Ion species separation: [12], [16], [Herrmann], [Hsu],
Shock structure – single species	Planar steady-state solution [36]	Shock tube experiments [Hua] [Rinderknecht]
Shock structure – multi-species	Analytical solution in limit of large Peclet number [Hoffman]	Shock tube experiments [Hua] [Rinderknecht]
Moderate N_K (e.g. Knudsen reactivity reduction)		Fuel density scan in shock-driven implosions [10]
Large N_K (collisionless plasma)		Ion thermal decoupling: [16] Collisionless counterstream: [39], [LePape].
Magnetic field generation		Laser-bubble experiments: [40, 41]

Table 2: List of test problems and experimental datasets for the proposed verification and benchmarking efforts

	Hydro+	VFP	PIC
Codes	**ZPKZ [Zimmerman, Hoffman, Ho]** xRage [LANL]; Miranda [Cabot]; DUED [Atzeni]; …	**iFP [Chacon, Taitano]** FPion [Larroche]	**LSP [Voss/Thoma]** OSIRIS [Mori] VPIC [Fernandez] ePLAS [Mason]
Status	Verification & validation phase	In development	Radiation package added
Challenges	Robust N-species treatment? Agree upon models?	Lacks radiation drive; Verification underway	Significant verification required
Timeline for credible integrated study	**~ 6—12 mo**	**2—3 yrs**	**1—2 yrs**

Table 3: Existing code capabilities, with status and potential timeline for integrated ICF study using the bolded examples in each category.

Several recent design advances implemented in the code iFP reduce the computational burden of the VFP approach and put full ICF simulations within reach, as described in Section II [Chacon][Taitano]. This code is in the development and verification stage, and currently lacks several features necessary for integrated ICF simulations, namely, radiation transport, laser ray-tracing, and burn diagnostics, which are tentatively scheduled to be added in 2017 depending on demand and physics interest. These needs project the timeline for believable integrated ICF studies using VFP to 2—3 years. Some partial studies of fuel dynamics and hohlraum plasmas will be possible over a shorter timeframe. In particular, as an outcome of this workshop iFP and FPion simulations of the fuel in D^3He-gas filled implosions will be compared in detail during 2016.

b. "Experimental Pathway": Integrated scaling experiments sensitive to kinetic physics in ICF

Scaling experiments, in which a single parameter of the experimental design is varied to change the likely impact of kinetic physics in the plasma, provided the most comprehensive experimental datasets presented at the workshop [Rosenberg] [Herrmann] [Casey] [Rinderknecht]. Although the explicit impact of the kinetic physics on observable effects may not be known a priori, the trends in all observables as the experiment is varied from "hydro-like" to "kinetic-like" provide a rich database for understanding where hydrodynamics breaks down and testing hypotheses about the resulting conditions.

We propose to perform integrated scaling experiments that study kinetic physics mechanisms in ignition-relevant targets on OMEGA and the NIF. Proposed studies are described below in order of the region being explored, from the LEH inward to the fuel. The studies are based on existing experimental platforms to reduce development time.

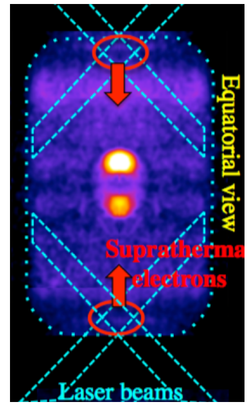

Figure 1: x-ray emission from hot electron preheat of a surrogate Bi capsule. From Ref. [1]

i. Image hot electron preheat vs time – Published research measured the hot electron preheat during the laser picket by imaging hard x-rays produced on the surface of a surrogate Bi-coated capsule [1]. These images showed asymmetric preheat, with the poles more strongly heated than the equator, in hohlraums with high- and moderate-gas fill, as shown in **Figure 1**. Further studies probing the energy and symmetry of hot-electron preheat later in the laser pulse may be performed by successively burying the Bi layer at a depth that will remain unablated at the time of interest, and will provide a time- and space-resolved measurement of this non-local source for implosion asymmetry.

ii. Hohlraum interior conditions – Varying the fill gas pressure of the hohlraum from high pressure (1.6 mg/cc) to near-vacuum (0.03 mg/cc) produced changes in absolute energy coupling, backscatter, and hot electron preheat. Dot spectroscopy measurements have been used to measure electron temperature (T_e) on the axis of hohlraums with 0.96 mg/cc, as shown in **Figure 2.** While the T_e was accurately modeled, the position and expansion of the dot was not. Dot spectroscopy probing of the hohlraum interior conditions as a function of hohlraum gas fill pressure and at angles around the capsule will provide valuable information for understanding kinetic physics in the hohlraum.

iii. Proton radiography of NIF hohlraums – Proton radiography has demonstrated megaGauss magnetic fields near the LEH and GeV/m electric fields perpendicular to the hohlraum wall in OMEGA experiments [Li]. The proton radiography diagnostic is now available on the NIF [42], and will provide valuable time-resolved measurements of hohlraum electric and magnetic fields as a function of hohlraum gas fill and drive conditions. These measurements will constrain the scale of B-field modifications to heat transport, as well as ion species concentration, in the hohlraum gas/wall interface and near the LEH.

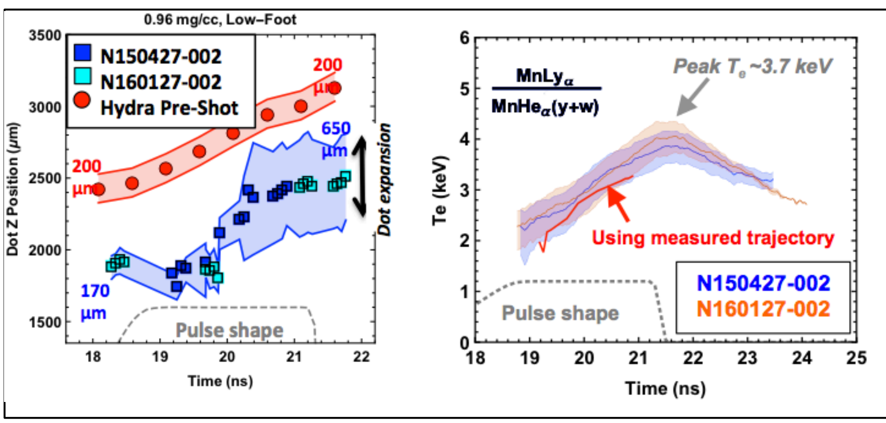

Figure 2: Position and T_e inferred from dot spectroscopy experiments of hohlraum conditions on NIF. [Barrios]

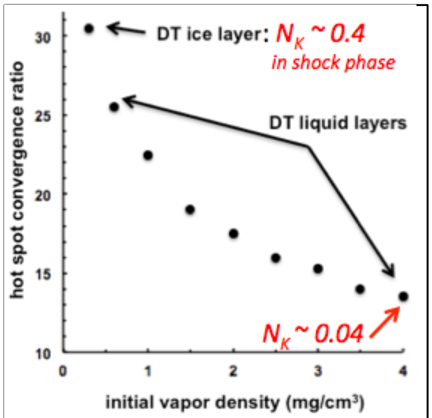

Figure 3: Initial vapor density vs. convergence for wetted foam DT-layered implosions [Olson]

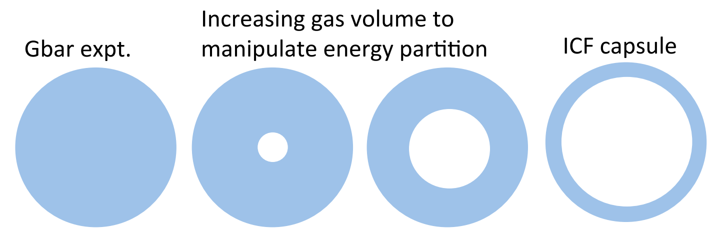

Figure 4: Cartoon of DT-ice layer in "DT-Gigabar" scaling experiment, varying from solid ball to ICF. [Ping, Gaffney, Rygg]

iv. Vary hot-spot initial conditions using DT-vapor density – The initial density of the DT-vapor (~0.3 mg/cc) is set by the vapor pressure of DT-ice near the triple point. By absorbing liquid DT in a foam layer, a near-solid density DT layer can be formed in the capsule while varying the vapor pressure with target temperature by an order of magnitude, as shown in **Figure 3** [Olson]. This variation directly reduces the Knudsen number of the DT-vapor during the shock phase, testing whether kinetic physics during this phase affects hotspot formation. Wetted-foam experiments have begun on the NIF. Impact of the wetted foam on implosion behavior may confound the results and must be carefully considered.

v. "DT Gigabar" platform for hotspot formation dynamics – Energy transport processes in the hotspot have different dependencies on scale length: radiation, e-i equilibration, and fusion processes vary with volume (L^3), conduction with surface area (L^2), and Knudsen number and stopping power effects with radius (L). A series of experiments starting with a solid DT-ice ball, similar to the "gigabar" experiments using a solid target [43], and varying the aspect ratio of ice to vapor region as shown in **Figure 4** will probe the scaling of the hotspot physics.

These two proposed paths to quantify the impact of kinetic physics in ICF experiments on the NIF complement each other. Improved capability and benchmarking of kinetic physics codes at several levels of physics fidelity will verify the sensitivity of the experimental studies to the physics of interest. Development of the experimental campaigns will test the predictions and discriminate between the simulation approaches.

IV. Findings and Recommendations

A. Identified anomalies in NIF dataset – The workshop finds important anomalies in the NIF dataset are potentially caused by kinetic physics, including: energy missing from the hohlraum drive (10—30% of laser energy); low-mode drive asymmetry in near-vacuum hohlraums; simulated ρR systematically 10—20% higher than observed; simulated neutron burn-averaged $\langle T_i \rangle$ systematically 20—30% lower than observed; ratio of $\langle T_i \rangle$'s inferred from DD- and DT-neutrons observed to be larger than is explained by known hydrodynamic mechanisms; and ratio of neutron yields from the DD and DT reactions observed to be lower than expected by up to 40%. These anomalies appear to systematically reflect the effects of physics not modeled by 2D, and in some cases 3D, single-fluid hydrodynamics. Determining whether the effects of kinetic physics in the hohlraum or the fuel can explain these results is a top-level goal for the proposed kinetic simulation efforts.

B. Identified sensitive ICF components – The workshop finds several component phenomena in indirect-drive ICF are likely to be influenced or dominated by kinetic physics, with potential effects on the ignition margin of the experiment. These phenomena are, in order of estimated severity of impact: magnetic and electric fields in hohlraums and the fuel; time- and space-dependent hot e- production; multispecies effects within the fuel; non-thermal physics within the DT vapor; shock structure in the DT vapor; interpenetration in the hohlraum/gas interface; Knudsen layer effects in the fuel; phase change dynamics causing localized condensation of the ablator; multispecies effects within the hohlraum wall blowoff; multispecies effects at the ablator/DT interface; and multispecies effects in the ablator. The effects of these phenomena should be estimated and investigated by simulation in priority order. Experiments to better understand the physical mechanisms and evaluate their impact for ICF should be considered.

C. Create testing and benchmarking database for kinetic codes – The workshop recommends the assembly and active development of a database of test problems and experimental results in fundamental plasma physics for the testing and benchmarking of advanced physics codes. Data and analytical solutions should test fundamental physics ranging from hydrodynamics to fully kinetic physics, as described in Table 2. Experimental data should be drawn from published works and include sufficient information to constrain and benchmark the physics models relevant to ICF. This database will provide a means for confirming the accuracy of codes and facilitate comparison between codes with different levels of physics fidelity.

D. Work towards fully kinetic ICF simulations – The workshop recommends that the ICF Program consider work towards simulations of ICF components and full ICF implosions using advanced kinetic codes. Three approaches with varying physics fidelity have been identified as promising candidates for kinetic ICF simulations in the next three years, as described in Section III a. Development, testing, and comparison of these three approaches are critical for understanding the source and impact of kinetic physics in ICF.

E. Perform integrated scaling experiments sensitive to kinetic physics – The workshop recommends that the ICF Program consider integrated scaling experiments to directly probe the importance of kinetic physics in ICF-relevant experiments. Several proposed studies described in Section III b leverage existing experimental platforms on OMEGA and the NIF, allowing rapid generation and evaluation of the results. These experiments will provide much-needed data regarding whether the kinetic effects observed in experiments at smaller facilities scale to indirect-drive ICF as performed on the NIF.

F. Reconvene in two years to assess progress – This document defines a path toward quantifying the impact of kinetic physics in ICF. The workshop recommends that a follow-up workshop be convened after two years, to evaluate progress, incorporate the results of new research, and conclude whether kinetic effects significantly impacts ignition margins.

V. Works Cited

References with names only refer to the presentations at the workshop. Versions of many presentations have been released for general distribution, and are available online at: https://lasers.llnl.gov/nif-workshops/kinetic-physics-workshop-2016. The password for locked presentations as well as unposted presentations are available upon request.

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