LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-692518

High-foot Implosion Workshop (March 22-24, 2016) Technical Report

O. Hurricane

May 19, 2016

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Lawrence Livermore National Laboratory

High-foot Implosion Workshop (March 22-24) Report

Lawrence Livermore National Laboratory

May 6, 2016

LLNL-TR-692518

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

Introduction

From March 22-24, 2016 at Workshop was held at Lawrence Livermore National Laboratory bringing together international experts in inertial confinement fusion research for the purpose of discussing the results from the 'high-foot implosion campaign.' The Workshop topics covered a retrospective of the first two years of experiments, a discussion of our best present understanding of what the data and our models imply, a discussion about remaining mysteries that are not understood at this time, and a discussion of our strategy moving forward.

The material herein contains information from published and unpublished sources and is distributed solely for the purposes of this Workshop.

Key assessments and conclusions resulting from the Workshop are:

"The high foot campaign is extremely well documented and the interested reader is urged to go directly to the peer-reviewed journal literature for details." – D. Haynes (LANL)

"Overall progress in understanding of fuel and hot-spot properties near peak burn is excellent." – V. Goncharov (LLE)

"I would say that given the constraints of using the same hohlraum and similar capsule designs to the National Ignition Campaign, the High Foot Campaign achieved as much as could be expected. Indeed the demonstration of significant alpha particle heating remains a landmark achievement." – J. Chittenden (Imperial College)

"One of the principal points of discussion at the meeting was the importance of the roll over in inferred pressure that occurs with reducing coast time for different ablator thicknesses and the idea of repeating shot N140819 to confirm this. I would be very interested to see a return to the High Foot platform as a way to exercise the improved radiographic capabilities such as the curved crystal imaging system and as a way to examine the hypothesis of 'burn truncation by aneurism.' " – J. Chittenden (Imperial College)

"It is clear from the quality of the data presented during this workshop that the High-Foot experimental series has been a success. It has fulfilled the original goal of being an implosion platform that could separate the low-mode effects from the high-mode effects. Just because we now know when the High-Foot implosions break, it does not mean that they have served their purpose. This will be a very useful platform to study hohlraum coupling, to determine if controlling shape reduces residual kinetic energy, and testing hypotheses of how the hot-spot assembles." – J. Knauer (LLE)

"The LLNL "base camp" strategy for hohlraums was finally presented. Goals are to understand the safe operating space for the hohlraum and to find designs with good enough symmetry inside

NIF's envelope, varying the CCR, pulse length and capsule designs. LLNL has a draft set of drive asymmetry requirements." – P. Gauthier (CEA)

Session #1

The high-foot implosion campaign – history, observations, and strategy

Presenter: O.A. Hurricane & Moderator: D. Haynes

Summary:

- *The high-foot implosion campaign developed a more robust implosion that was used to scan performance over a range of implosion speeds, demonstrate a yield doubling from alpha heating, and demonstrate the highest levels of ICF implosion performance, as measured by yield and stagnation pressure, to date. The campaign also probed a performance cliff at high velocity that appears to be unassociated with mix.*

Key points from presentation

- The original high-foot (HF) design used the same hohlraum and capsule as was used in the NIC, modulo a higher He gas fill in the hohlraum (1.6 mg/cc vs. 0.96 mg/cc).
- Most HF DT shots were used to test three ablator thickness over a range a laser energy in order to scan performance over a range on velocity from 300 km/s to 390 km/s.
- The best performing HF DT shot so far obtained 26 kJ of fusion yield (with 2.3x in yield multiplication from alpha-heating) and a ~230 Gbar stagnation pressure.
- Systematic behavior of HF DT performance was observed as a function of laser energy (i.e. implosion speed and coast-time).
- Repeatability of burn-average stagnations metrics was demonstrated.
- HF implosions scanned a range of convergence ratio's (CR's) of 26-38 (in terms of CR to hot-spot) or equivalently 13-23 (in terms of the ablator-fuel interface).
- Picket hot-electrons observed early in the campaign were mitigated by adding a time delay between the inner and outer NIF beams.
- Other issues noted early in the original campaign, such as late-time hot-electron, an out-of-spec P4 shape, and hydro-perturbations caused by the tent capsule mount are only being addressed now.
- Observations from multiple diagnostics of HF DT shots indicate that the stagnation of the fuel departs from 1D.
- A number of other more mysteries remain unaddressed at this point in time.

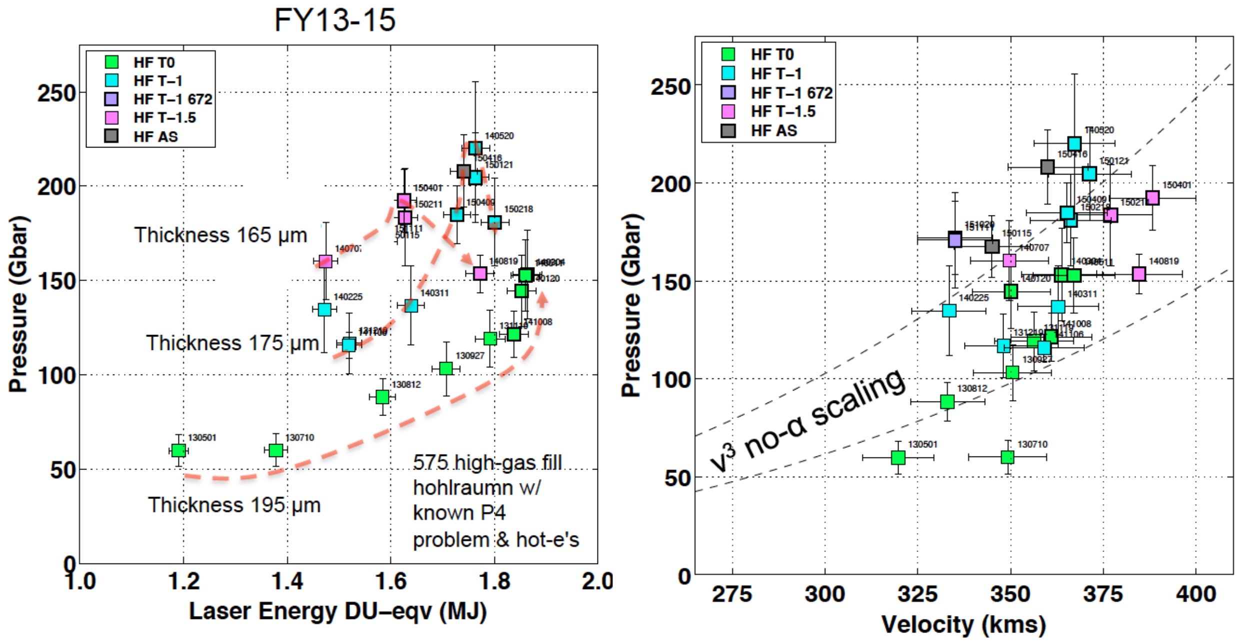


Figure 1: High-foot implosion hot-spot inferred pressure responds to laser energy and implosion speed is a systematic fashion.

Moderators documentation

The high foot campaign is extremely well documented and the interested reader is urged to go directly to the peer-reviewed journal literature for details (ed. see Appendix B). This narrative is intended to highlight some of the trends that the team observed and to capture the comments and questions that arose during Dr. Hurricane's introductory presentation to the High Foot Workshop on March 22, 2016.

Motivated by the observed performance of the NIC implosions, the team sought a 'more forgiving' implosion, an implosion whose performance was robust in the face of poorly understood or poorly controlled phenomena. Three desiderata were that, compared to the NIC design, the implosion should achieve lower convergence ratios while being less susceptible to ablation front RT instabilities and avoiding an uncertain region in C EOS during the lengthy trough of the laser pulse. For practical reasons they initially used the NIC hohlraum and capsule. This left them with the hohlraum gas fill and laser parameters (pulse shape, delta lambda, and pointing) to control. Compared to the NIC pulse shape, the resulting "high foot" pulse shape has a higher picket, a higher and shorter trough, and one fewer shock. Using the hohlraum and implosion characterization tools developed during NIC they designed and tuned the high foot pulse shape over the course of 9 shots. The resulting DT implosion appeared close to 1D prediction with reasonable hot spot symmetry and the hohlraum responded in a similar fashion to the experience built up during the NIC. This seemed like a reasonable candidate with which to push to higher velocities to test scaling and to explore performance cliffs.

The ~25 DT layered shots can be thought of as being divided into three mini-campaigns each of which used a different ablator thickness. For each change in ablator thickness a few non-DT-layered shots were used to tune up the implosion. Within each of these mini-campaigns the power and duration of the main pulse of the laser was varied. Concomitant changes in delta lambda were used to influence the evolution of the shape of the imploding assembly. At the end of each of the mini-campaigns the Au hohlraum was replaced with an Au-coated Du hohlraum to increase the drive.

During the first mini-campaign (with an ablator thickness of 195 microns), the team started with a relatively conservative laser pulse. On May 1, 2013, the first DT shot of the campaign performed very well when compared to the best NIC implosions with a fairly round implosion and a yield within a factor of two of today's simulation. The next shot increased the power of the main pulse and the performance improved, but the equator was under-driven and the shape became noticeable oblate. After an abortive attempt to fix the P4 shape by going to a longer ('+700') hohlraum, the team reverted to the original hohlraum and added energy to the system by going back to the old peak power and extending the duration of the main pulse. This resulted in the first laboratory DT implosion in which alpha heating contributed significantly to the observed yield. The team then increased the power of the main pulse while keeping the duration fixed and the performance steadily increased up until the point that the limit of the NIF laser's ability to deliver energy to the hohlraum was reached. The team then turned to Au-plated DU hohlraums to get about a 6.5% increase in drive. The resulting shot, at the limits of the laser and the periodic table, gave an implosion with a fairly round hot spot (ed. the hot-spot shape was improved as compared to Au hohlraum shots, but still distorted) with a fusion neutron yield of 9.3e15, of which half was due to the effects of alpha heating. During this 195 micron mini-campaign it was noted that the capsule implosions performed best that coasted least. This fact, and the fact that performance is a strong function of velocity, led the team to field capsules with thinner ablators. The two campaigns that followed had ablator thicknesses of 175 microns and 165 microns. For a given laser energy, thinner ablators performed better than thick ablators both in terms of shape and neutron yield. However, for all three ablator thicknesses the peak performance was the same, it was just arrived at lower energies for thinner capsules. When even higher energies were used, the performance suffered and the inferred hot spot pressures decreased.

Along with the aforementioned observation about the anti-correlation of coast time and performance, there were several other important trends observed during the campaign. The FNADS indicate a common pattern of inhomogeneity of the fuel rho-r, with 'polar ice caps' and two high rho-r continents on the equator. None of the implosions exhibited the anomalous xray yield used to infer mix of ablator into the hot spot. These observations have led to a hypothesis that performance is limited by the loss of confinement of the burning hot spot material though aneurisms that evolve very rapidly during the duration of the burn. The thin spots that seed the aneurisms are thought to result from flow of shell material seeded at very early times and amplified greatly by convergence ratio effects. This hypothesis could well form the basis of a targeted experimental campaign moving forward.

During Dr. Hurricane's presentation there were several colloquies concerning the experimental results and trends. The next few paragraphs try to capture the information in theses exchanges.

The trough temperature was raised such that the carbon ionization stage was firmly in the K shell. There was discussion about whether the anomalous double shock structure predicted at lower temperatures was a result of a bug in the non-LTE simulation package. Tom Dittrich said that it was not. Jerry Chittenden remarked that the anomalous double shock structure is seen in his simulations of the low foot NIC experiments but not in simulation of the high foot. The ability of VISAR to determine whether or not such anomalous shocks exist in nature for keyhole experiments was questioned but it was decided that, because VISAR only sees the velocity of the foremost shock, the effect of the double shock would not be observable on VISAR. This assertion was questioned by Bedros Afeyan in the sense that VISAR might nevertheless agree with one scenario or the other (ed. Assumes x-ray drive is precisely known, which it is not).

Based on HGR data, we now know that we are able to accurately calculate the growth of relevant-mode ablation front instabilities for the low- and high-foot designs to a convergence ratio of 2. At the inception of the high-foot campaign, this wasn't known and the pulse shape was chosen to provide insurance against this uncertainty. Growth = seed * growth factor, so the fact that we know that we calculate the growth factors somewhat correctly and the fact that we know the smoothness of the capsule to a gnat's eyelash together imply that there is a seed that is not surface roughness (ed. for example the 'tent'). It is currently speculated to be an uneven distribution of embedded oxygen atoms introduced during curing. This is being actively investigated.

The question of whether the effects of low-mode and high-mode asymmetries could be 'diagonalized' was raised. It was said that they could be for moderate convergence ratio implosions, but Dan Clark noted that the interaction of the large perturbation from the tent with asymmetry was notable.

A member of the workshop asked whether HGR had been performed for the adiabat shaped pulse, whether it had been demonstrated that ablation front stability and fuel adiabat could be controlled separately. The answer was yes, and a reference was mentioned [ed. Robey, H. et al., 23, 056303, doi:10.1063/1.4944821 (2016)]. After the session Harry Robey added that the picket is the dominant knob in controlling ablation front instability and the trough strongly controls fuel compression (affecting adiabat and DSR). These can be controlled separately, as demonstrated in Clark, et al., PoP 21 112705 (2014) and Robey, et al., APS/DPP invited talk (2015).

The impact of the tent was discussed. Dr. Hurricane was asked what he thought was most important impact of the tent. He said that he believed it was the degradation of the confinement of the hot spot.

Don Haynes questioned whether we had sufficiently demonstrated the correlation of 'anomalous xray yield' and mix and suggested using existing data from implosions using deuterated methane or the marble targets where the bulk of the C in the core is known in advance. Also, recent 3D simulations of the NIC indicate that there is a significant solid angle of the core for which the xray emission is not occluded by any dense shell material, while simulations of the high foot do not postdict any 'naked' core. Does this phenomenon confuse the correlation of 'mix' with xray yield as measured from a certain angle. The team should forward model what the xray yield diagnostic would have seen from these simulations.

Don Haynes also pointed out that mix of what we think of as cold fuel with what we think of as hot spot is not measured or inferred from the xray yield technique.

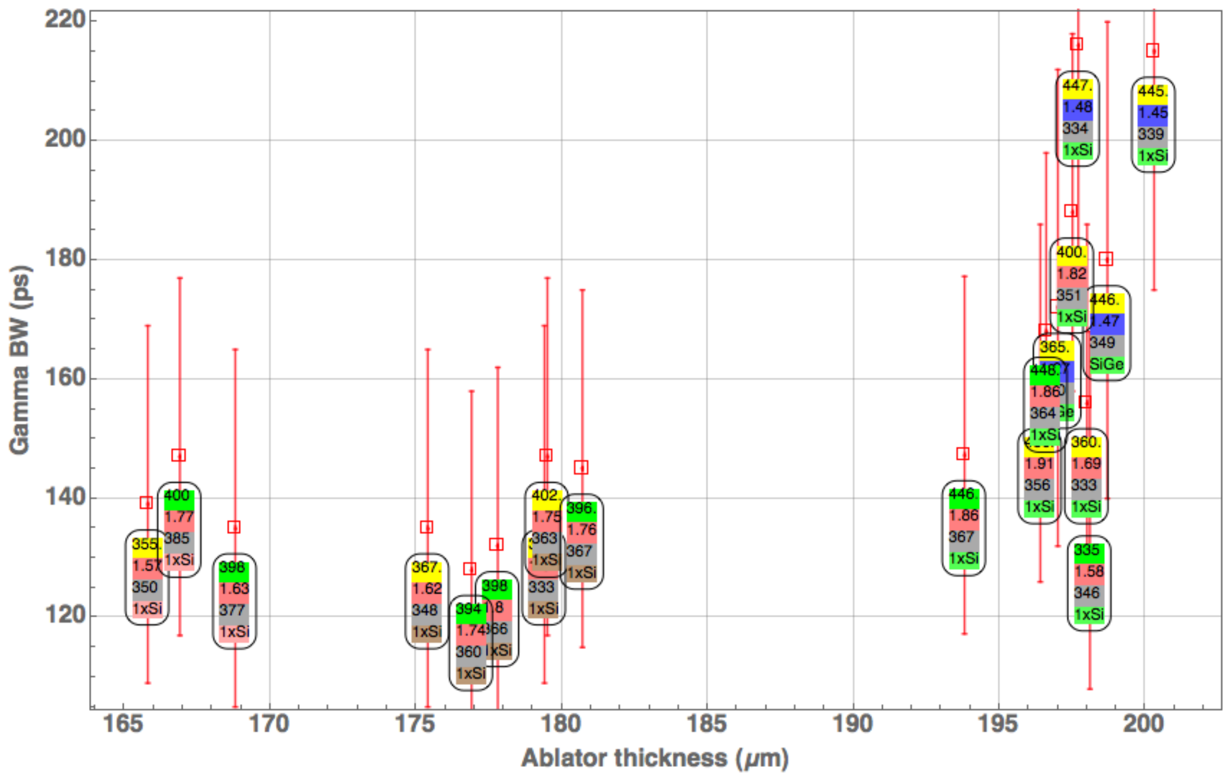
Dr. Knauer said that the results that were presented indicated that symcaps are poor surrogates for DT-layered implosions. It was suggested that they might be fine surrogates but that they are diagnosed at 200 microns, too early for the image obtained to correlate with the late time configuration (ed. Correction: Symcaps are gas capsules that give the hot-spot shape at peak compression. 2DConA's are gas capsules that give the shell shape at 200 microns, but also give the hot-spot shape at peak compression). Later in the discussion, the surrogacy of keyholes and thus their utility in setting shock timing was questioned given the results of the 175 micron thick ablators compared to results from the other two thicknesses (ed. high-foot keyhole experiments indicated that the length of the trough as measured for the 175 micron case is not what one would interpolate from the keyhole experiments of the 195 and 165 micron cases – this fact remains a mystery).

The failed attempt to improve symmetry by going to a slightly longer hohlraum was briefly discussed. Our inability to predict the evolution of the gold bubble and the LPI (CBET and SRS in particular) impacts during the inner beams' 1mm transit were mentioned as possibilities. Dr. Edwards reminded the workshop that there was a lot going on in all gas-filled hohlraums that we do not understand and so that is was not surprising that the effects of modification of the hohlraum geometry were hard to predict.

Dr. Goncharov commented on the hypothesis that the thin spots in the main fuel and remaining ablator (developed as "bubbles" during the deceleration RT instability) rupture the shell and let the hot spot "leak" out. This phenomenon should strongly depend on shell thickness and convergence ratio. In particular, the initial shots in HF campaign with a significant coasting phase should experience very little degradation due to this effect since the shell density gets relaxed and shell thickness increased prior to deceleration (ed. in fact this seems to be the case going by the agreement with between data and 1D simulation).

When ablator thickness gets reduced, on the other hand, the bubbles should break out of the shell earlier. So performance degradation should be more pronounced for thinner ablators (ed. this also seems to be the case gauging by discrepancy between data and 1D simulation). I think Dr. Hurricane claims that thinner ablators have smaller long wavelength nonuniformity which cancels out earlier bubble break out phenomena (ed. that is, if the non-uniformities that could grow into aneurisms are reduced, their onset can be delayed). This can be checked with simulations. Dr. Hurricane answered that what matters for aneurisms is not the initial thickness but rather the amount of remaining ablator mass at bang time.

Jim Knauer asked to see gamma reaction histories. Omar said that the observed trends were that distorted implosions had longer burn durations, and that thinner shells had shorter burn durations (ed. To avoid confusion from qualitative statements a plot, *unpublished,* is provided below.)



During the discussion of the T-1 replicate variability study it was noted that the tight DSR error bars reported seemed inconsistent with the +-10% variations in rho-r as measured by the many FNADS (ed. FNAD is much more directional than nToF DSR's which sample a large solid angle. Moreover, the angular variation of nToF DSR's can actually be larger than the quoted error bars).

The team was urged to repeat 140819 exactly (but without the 'buckle'). (ed. 140819 was the HF shot with a 165 micron ablator and extremely short coast-time of ~150 ps, but suffered from a defect in the as-built ablator)

We briefly discussed the impact of uncertainties in the meaning of T_{ion} inferences, but this will be covered in great detail tomorrow (ed. Session #4).

Dr. Landen notes that bubbles due to P2 or P4 seeded RT growth happen late in time (last 100 ps), unlike tent feature. Thin DT shell that is only 7 μm wide to begin with (hard to see with first CR shots) will thin easily. Very different from tent holes formed early, so we break degeneracy. But complication is that tent is at same location as P4 bubbles. So perhaps an experiment to test hypothesis with tent alternative in place is DT performance with and without P4 (just by change in length of hohlraum)?

Session #2

Hot-spot and cold fuel conditions at stagnation - Data

Presenters: P. Patel, G. Grim, C. Cerjan, D. Casey & Moderator: V. Goncharov (LLE)

Summary:

- *Data of high-foot implosions at stagnation imply systematic behavior as a function of implosion speed, but the implosions do not appear to be 1D in some respects.*

Key points from presentation(s)

- Burn-off yield scaling with implosion velocity appears to follow expectations.
- Burn-off Tion scaling with implosion velocity is higher than expectations – possibly due to Doppler broadening of the NToF signal (i.e. residual kinetic energy, RKE).
- Burn-off yield scaling with Tion is lower than 1D theory [e.g. Betti, R. et al., Phys. Plasmas, 17, 058102, (2010)]
- Nuclear P0 (hot-spot radius) and X-ray P0 are correlated and consistent with each other to within error bars for all but one DT shot (the first high-foot shot, N130501).
- The levels of DSR deviation from 1D varied by as much as 50% for the NIC, whereas for the HF the deviation was reduced to 15% levels.
- As inferred from fluence compensated neutron imaging, most HF implosions appear to have asymmetry in the cold fuel at stagnation, with fuel often collecting near the poles of the implosion.

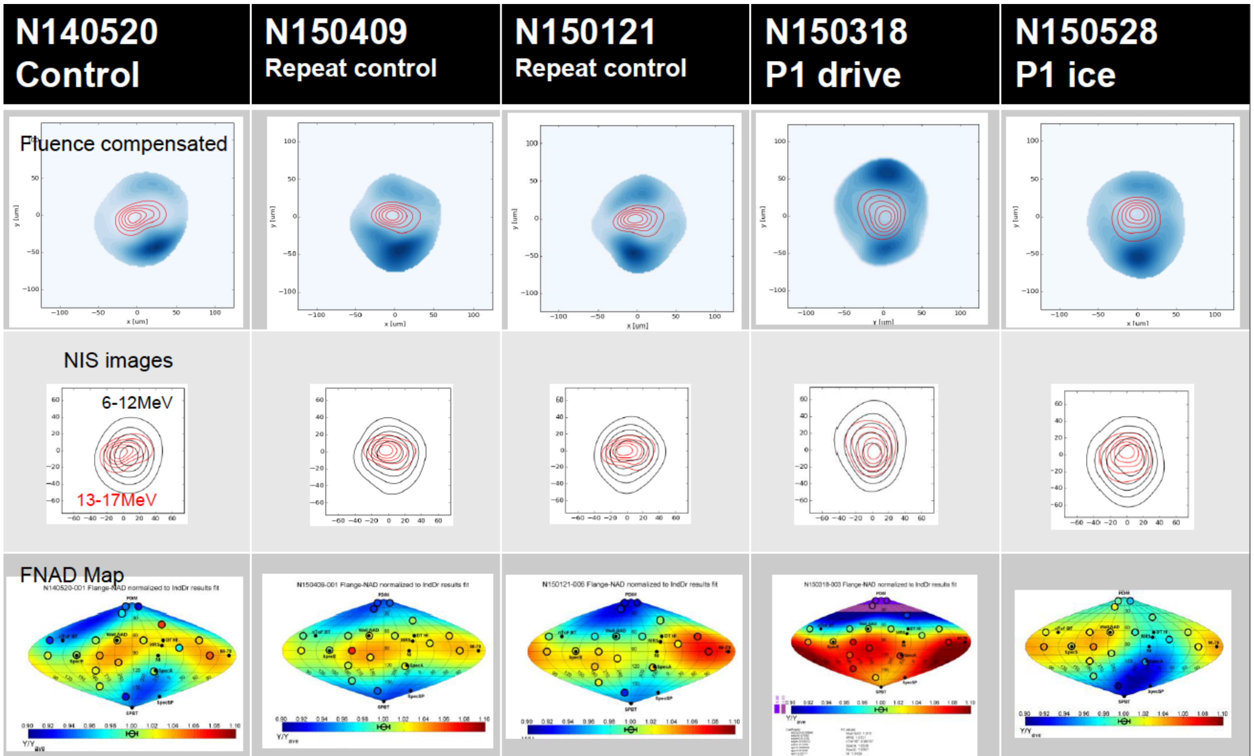


Figure 2: Fluence compensated down-scattered neutron images and FNAD maps generally imply the existence of polar ice caps at peak compression.

Moderators documentation

The discussions during Session #2 of the High-Foot workshop focused on post-shot analysis of hot-spot and cold fuel properties at stagnation.

Overall progress in understanding of fuel and hot-spot properties near peak burn is excellent. The introduction on post-shot analysis was given by Pravesh Patel. The highlights are the following:

- 31 shots were taken in the high-foot campaign (ed. technically some shots taken using the high-foot pulse-shape were under the auspices of the ‘stagnation campaign’ and others under the ‘adiabat shaping campaign’). The results were organized based on velocity-like metric proposed by D. Callahan [Phys. Plasmas 22, 056314 (2015)]. Several fits were shown of target yield vs. velocity parameter. When the yields were reduced based on calculated burn-off fraction, a $Y \sim V^{5.6}$ scaling (ed. V being peak implosion velocity) was derived from the data, which is close to a 1-D $Y \sim V^6$ dependence.
- **Comment: It is not clear from the presentation if quality of the fits is good or not. There is a big scatter of the data at higher laser energies. Also, an error bar must be given for the power index.**

- Fitting DT ion temperature inferred using Brysk analysis leads to a $T_i \sim V^{1.8}$ scaling, which shows a stronger velocity dependence than 1-D scaling $T_i \sim V^{1.2}$. The issue was raised that the measured ion temperature is affected by broadening due to fuel motion.
- **Comment: Is stronger temperature dependence on velocity an indication of stronger non-uniformity flow in higher velocity implosions?**

- X-ray burn width shows a reduction for the latest shots with a reduced ablator thickness (T-1, T-1.5 implosions). There are also some indications that X-ray width is systematically shorter than nuclear BW for these shots (ed. The GRH measurement is suspect, since it never indicates burn widths < 130 ps).
- **Comment 1: The burn width in 1-D scales as R_{hs}/V_{imp}. As the implosion velocity increases with a reduction in ablator mass and hot-spot gets smaller, it is expected some reduction in burn width. Are the observed trends consistent with this scaling?**
- **Comment 2: X-ray BW reduction could be instrumental for the latest shots. Change in filtering implemented in the thin-ablator shots leads to measuring higher x-ray energies. In addition, shell opacity is also changed as ablator gets thinner. Analysis of these effects must be performed to ensure that the observed trends are not instrumental.**

- **Comment: Mix in high foot experiments is inferred using x-ray core emission. Should some of the experiments, especially with thinner ablator, be repeated using Ge-doped shells to enhance sensitivity to ablator mix?** (ed. One Ge-doped shell HF implosion was performed, N130710, and the mix result was again null).

Gary Grim gave nice overview of his model of 1-D fuel assembly using neutron imaging. In particular, the model relates the measured size of neutron emission with DSR (called geometric DSR in the presentation)

- Using this model for low-adiabat NIC implosions shows higher DSR values (by as much as 50%) based on neutron imaging than the measured DSR for NTOF. The agreement between measured and geometric DSR is improved in high-foot implosions. Still geometric DSR was larger by 10% to 15%.
- **Comment: Could effects of tent cause this discrepancy?**

- Charles Cerjan presented qualitative summary of the high-foot campaign from stagnation diagnostics.
  - The presented model, based on ^{12}C-γ GRH signal, extends an existing stagnation model to include the compressed ablator.
  - The model infers higher ablator density at stagnation for lower-adiabat NIC implosions relative to the recent high-foot, higher-adiabat designs.
  - **Comment: This makes sense from 1-D physics, but not so obvious when target non-uniformity growth is taken into account. NIC designs show much larger perturbation growth factors which should lead to ablator decompression. Is the inferred ablator density consistent with 3-D calculations?**

- Detailed comparison of model predictions using 3-D simulations with measured fNAD ratios shows quantitative (ed. qualitative) agreement.

Dan Casey discussed very interesting new technique to infer cold shell geometry near peak compression based on neutron fluence compensation and forward-fit density reconstruction of NIS down-scattered images. Currently, there is a knowledge gap in position and uniformity of cold, compressed fuel layer near the peak neutron production. The presented technique shows very promising path of providing this valuable information.

- The technique is based on convolution of down-scattered neutron image with the primary neutron fluence. This enhances asymmetries caused by cold shell nonuniformities.
- Detailed comparison with the 3-D simulation results is underway.

Session #3

2D & 3D simulations of high gas-fill hohlraum high-foot implosions

Presenters: A. Kritcher, D. Clark & Moderator: J. Chittenden (Imperial College)

Summary:

- *Integrated hohlraum-capsule 2D simulations and detailed capsule only 3D simulations have been performed across most of the high-foot database of implosions.*

Key points from presentation(s)

- Integrated 2D hohlraum-capsule simulations appear to reproduce HF data in almost all respects (except P4 symmetry) for implosions with speeds less than 340 km/s when a single set of drive multipliers (calibrated to implosion trajectory and shock timing measurements) and a recipe for turning off CBET during peak power is used.
- Low mode symmetry effects become more important with increasing implosion speed.
- Yields scale with residual kinetic energy (RKE, a measure of non-stagnating fuel energy).
- Calculations indicate that neutron yield could be improved by factors of several if low mode asymmetries are mitigated.
- Asymmetric implosion can withhold ~1-2 kJ of kinetic energy from being transferred to internal energy of the DT and this becomes more impactful with increasing levels of alpha heating.
- Simulated DSR is high by 20-25% and simulated T_{ion}(DT) is low by 25-30% for experiments with implosion speeds > 340 km/s.
- High resolution detailed 3D capsule modeling appears to capture much of what the 2D model misses for the high velocity HF implosions.
- For the 3D model, the DSR and T_{ion} discrepancies are reduced to being just outside error bars.
- According to 3D simulations, the tent and hohlraum driven asymmetries are the largest sources of performance degradations.

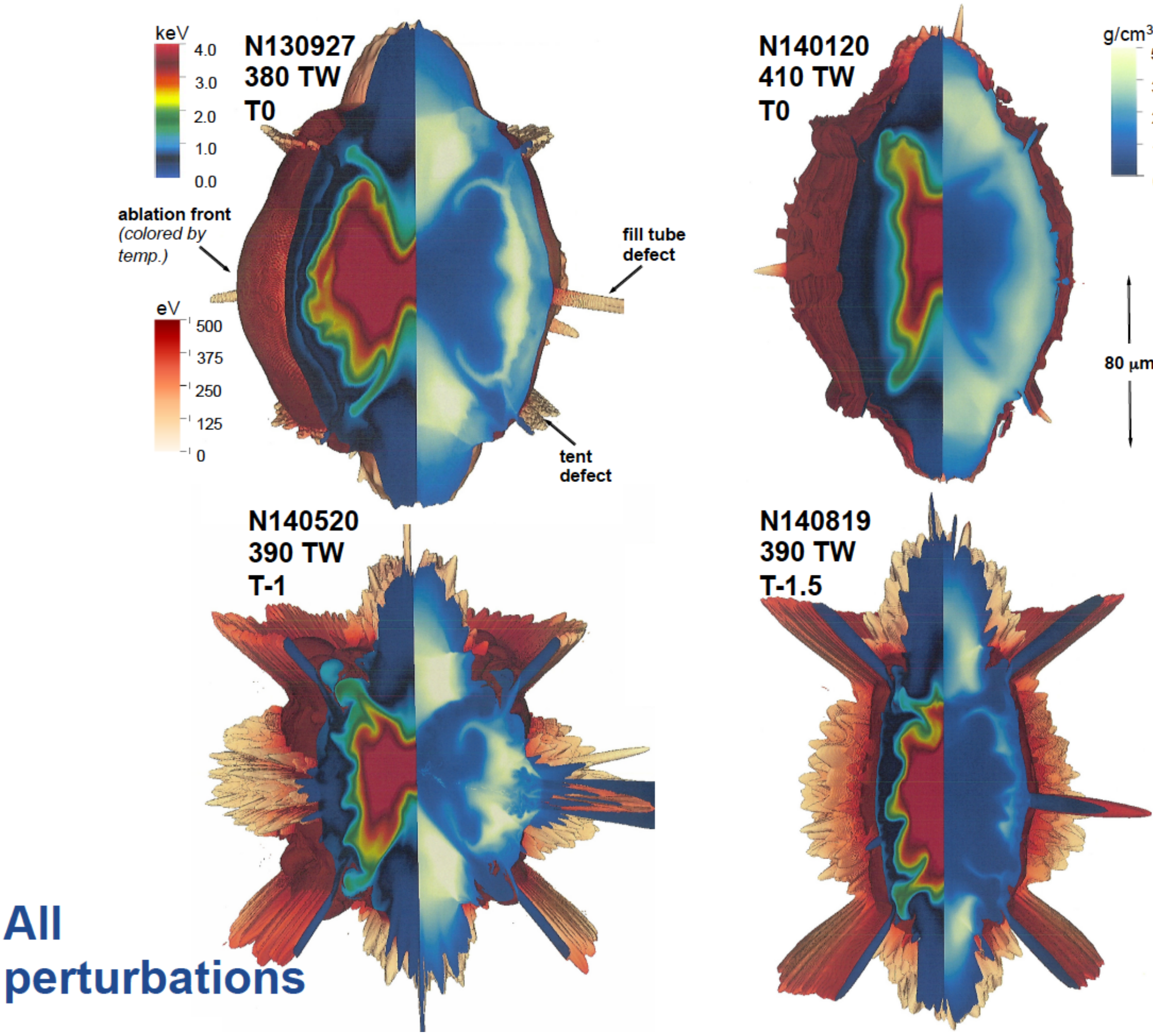


Figure 4: Hohlraum driven asymmetries and the tent perturbation are the largest sources of performance degradation.

Moderators documentation

Dr. Kritcher presented results from 2D integrated (holhraum and capsule) calculations. Unlike for the NIC low-foot data (where 3D high mode simulations (including tent) were needed to reproduce data), the high-foot data set is largely represented by 2D, low mode, post-shot, integrated simulations, provided that these match the observed shape. Deviations from agreement occur above 340km/s where large alpha heating is predicted, these differences are thought to be due to 3D and tent effects. These 2D simulations are run post-shot to include the measured capsule metrology and the measured laser pulses. Corrections due to backscattered laser light are included, but for layered shots these not measured directly but are inferred by scaling from companion tuning shots.

For the relatively high hohlraum gas densities used in the high foot campaign, the apparent experimental drive deficit compared to calculations requires the use of a number of empirically determined time-dependent drive multipliers to be applied to the laser pulse. In addition, the power balance between the outer and inner cones of beams is modified to take into account cross-beam energy transfer, using a semi-empirical model. The laser drive multipliers and the amplitude and saturation of the CBET model are constrained by shock timing and implosion trajectory measurements from companion shots as well as bang time measurements in the layered shots.

Dr. Haynes asked whether the physics behind the need for laser multipliers or CBET are benign and do not impact directly upon the capsule. Dr. Kritcher replied that SRS effects are only included through reduced laser powers in the hohlraum model. The effects of enhanced hot electrons can be included when large SRS is detected, although the level of fast electron preheat required to affect the DSR for example is very large. Where back scatter is measured to be larger, simulations don't match bang times as well. For some shots where the measured backscatter was high, the bang times were not as well matched using the same set of drive multipliers.

There was some discussion of the diagnostic data used to constrain the drive multipliers, particularly late in time. Dr. Goncharov asked whether the 1D conA data was dominated by the trajectory of the silicon dopant. Dr. Meezan replied that the DT was transparent to the back-lighter and that we rely on simulations to see if fuel is tamping the trajectory of the ablator. The conA follows the trajectory down to 150microns, beyond that the self-emission compromises the measurement close to axis. The capsule is coasting by this phase so it is earlier multipliers that we are calibrating with the late time motion. This phase is then further constrained by bang time measurements. Simulations appear to have larger velocities than 1D conA, but this lies within error bars. The shell may potentially be thickening faster than would be expected due to convergence, as a result of instability growth, but this is data again lies within error bars of simulation. Bang times could be sensitive to whether the shell is breaking apart in flight, but 3D simulations suggest that this introduces of order a 100ps difference compared to 1D.

For DU hohlraums, different cross-beam transfer saturation levels are required to match the data. For lower gas fill hohlraums the drive multipliers are less severe (although they remain finite). Dr. Chittenden asked whether we were assuming that all discrepancies were attributable to LPI and CBET and potentially unaware of inaccuracies in the radiation hydrodynamics results. Dr. Callahan responded that this was in part the motivation to wish to study hohlraums which are not LPI dominated, where the accuracy of the radiation hydrodynamics predictions can be tested directly.

Dr. Kritcher showed comparisons of P2 and P4 between simulations and 2D conA radiography as well as X-ray images. Matching the shape swing is improved by turning off the CBET at peak power. With these changes, the model predicts the shape and performance of capsules at < 340km/s fairly well, although the simulated DSR is ~25-20% systematically too high and the DT ion temperature is ~25-30% too low. Dr. Goncharov commented that if the burn is truncating earlier than predicted, then the neutron scattering is weighted by sampling lower average rho-R which could lead to lower DSR than predicted. Dr. Clark commented that 3D results are closer to the observed DSR due to large holes in the fuel layer and earlier truncation.

Dr. Kritcher went on to show how the ratio of measured to simulated yield can be related to the residual kinetic energy in the calculation. There was some discussion as to whether the loss of energy coupled to the hotspot was responsible for reduced performance or whether RKE is rather a metric or symptom of shape distortion. When the shape distortion is high, the RKE is high but there is also a lack of simultaneity in the inertia applied to hotspot, along with increased losses due to increased hotspot surface area and a loss of confinement late in time. Perhaps these separate contributions can be quantified in simulations.

Whilst the simulations predict the performance well for shots below 340 km/s there are some shots above this velocity which were also matched. The largest deviations from predictions come when the simulations predict large alpha heating factors (4,5, or 7 compared to < 2.5 for cases where predictions agree), i.e. it may be the start of ignition in the simulations which is responsible for the increasing discrepancy. Results may thus be sensitive to the alpha deposition model in these simulations. A suggestion is that alpha heating is raising the hotspot pressure significantly in these simulations, but that in experiments and in 3D simulations with the tent features included there are weak points in dense fuel which allow the hotspot to break out once its pressure is raised.

Using RKE as a measure of asymmetry, Dr. Kritcher showed how the high-foot lies in a regime where relatively small improvements in shape can lead to significant gains in yield. The potential gains by fully fixing shape are large and become even larger when significant alpha heating plays a role at higher implosion velocity.

Dr. Clark gave a presentation on large scale, 3D, capsule only, calculations which was motivated by wishing to address; why does yield plateau, why are the predicted T-ion lower and DSRs higher than measured and what are largest sources of yield degradation ?
The 3D simulations do a better job of capturing the overall experimental results than the 2D, if radiation drive asymmetry, surface roughness and tent scars are all included. The individual contributions of each form of perturbations can be assessed by omitting them from the calculations.

The radiation drive asymmetry applied to the simulations is that derived from integrated hohlraum calculations and thus the accuracy of the 3D calculations is to a certain extent contingent on the accuracy of the drive symmetry and frequency dependent spectrum provided by the integrated hohlraum calculation.

The short wavelength perturbation is dominated by surface roughness (as opposed to ice roughness etc) and is included at the amplitude measured by metrology (without the need to be artificially amplified). Dr. Haan commented that volumetric oxygen content variation can amplify the effective surface roughness by 2-3 times. Dr. Clark replied that increasing surface roughness by this amount does in fact cause a significant change and is not needed by this model to the explain data. In discussion, the oxygen content variation originating from the capsule curing process was thought to be a patch effect, rather than across the whole capsule.

The tent scar is imposed artificially, based upon extrapolation of early time high resolution simulations of the tent contact by Bruce Hammel. This perturbation method is then benchmarked against HGR data (this benchmark is only for the low foot shots where the tent is more visible ?). It may be that a different radiation transport approach would change the ablation of some of the narrower features, by non-radial components of the radiation flow.

There was some discussion as to the relative importance of high and low mode asymmetries and the mechanisms by which they affect performance. Dr. Clark commented that in these calculations, the most significant influence on yield comes from low mode effects due to both the tent and the radiation asymmetry causing weak regions in the dense fuel which allow the hotspot to outflow and reduce the post stagnation confinement. Experimentally it is hard to distinguish the effect of the tent scar from P4 radiation asymmetry as they are superimposed, but this can be done in simulation.

The simulations still under predict the measured ion temperatures (even when the contributions of fluid flow to the neutron spectra widths are included) and over predict the DSRs (this is true of 1D design calculations, 2D integrated calculations and 3D 'kitchen sink' calculations). The ion temperatures in simulation can be readily increased by reducing the electron thermal conductivity. This improves the overall agreement and the trends with different shots. Whilst this is an understandable parameter to try changing, the physical justification for doing so isn't clear other than that the electron thermal conductivity at these conditions is not well established. Alternatively there may be other micro-physics uncertainties which could have similar effects, such as reduced electron-ion equilibration or reduced radiation loss rate (it would be useful to quantify thermal conduction versus radiation as the principle loss rates in simulation).

As a final (personal) comment, I would say that given the constraints of using the same hohlraum and similar capsule designs to the National Ignition Campaign, the High Foot Campaign achieved as much as could be expected. Indeed the demonstration of significant alpha particle heating remains a landmark achievement. The evidence that performance of the high foot design is limited by the time dependence of the radiation drive asymmetry and by the capsule support structures appears to be strong. The hypothesis that the ceiling in the yield is set by a loss of confinement due to weak regions of low fuel rho-R remains compelling and seems to be supported by simulations. It is important to remember, however, that at present there is no direct experimental observation of this process. Given the limitations in the symmetry of this design, the change in emphasis towards the development of a larger hohlraum with lower gas fill and towards alternative capsule support structures, seems quite understandable. The need to explore different ablators in order to be compatible with lower hohlraum gas fills will of course lengthen this development process. It remains to be seen whether the desired radiation symmetry can be achieved in a hohlraum which is capable of driving a capsule design which robustly ignites in 1D. Even if this is the case, the same process of weak points or aneurisms in the dense fuel layer may well arise from other forms of perturbation and may ultimately still prove the limiting factor in performance. This problem will become particularly acute at the threshold of ignition where alpha heating starts to raise the hotspot pressure. The capability to test this hypothesis is currently limited by the lack of radiographic data at radii less than 150 microns. The considerable improvements to the spatial and temporal resolution of imaging diagnostics that are anticipated on NIF in the near term do however have the potential to fill in this missing piece of the puzzle.

One of the principle points of discussion at the meeting was the importance of the roll over in inferred pressure that occurs with reducing coast time for different ablator thicknesses and the idea of repeating shot N140819 to confirm this. I would be very interested to see a return to the High Foot platform as a way to exercise the improved radiographic capabilities such as the curved crystal imaging system and as a way to examine the hypothesis of ‘burn truncation by aneurism.’

Session #4

Tion and DSR anomalies and the state of measuring Te in the hot-spot

Presenters: G. Grim, M. Gatu-Johnson, P.Patel, B. Spears & Moderator: J. Knauer (LLE)

Summary:

- *The ion temperature (T_{ion}) inferred from neutron time-of-flight diagnostics seems to be too high (by many 100's of eV to a keV) to be reflective of the true thermal temperature of high-foot hot-spots. Highly 3D implosion morphologies with complex flows and 3D scattering geometries the most consistent explanation at this point.*

Key points from presentation(s)

- We do not measure thermo-dynamic temperature, but instead rely upon a neutron spectrum, that is subject to Doppler broadening and scattering effects, in order to obtain a 'Brysk' temperature.
- Attempts to obtain a better estimate of the thermal temperature from the ratio of DT and DD neutron yields has been informative, but has not really come to closure.
- Efforts are now focused on obtaining an electron temperature measurement, which is expected to be more representative of the true thermal T_{ion} of implosion hot-spots.
- It is not understood why our measured DSR is lower than simulation expectations, but there are several hypothesis.

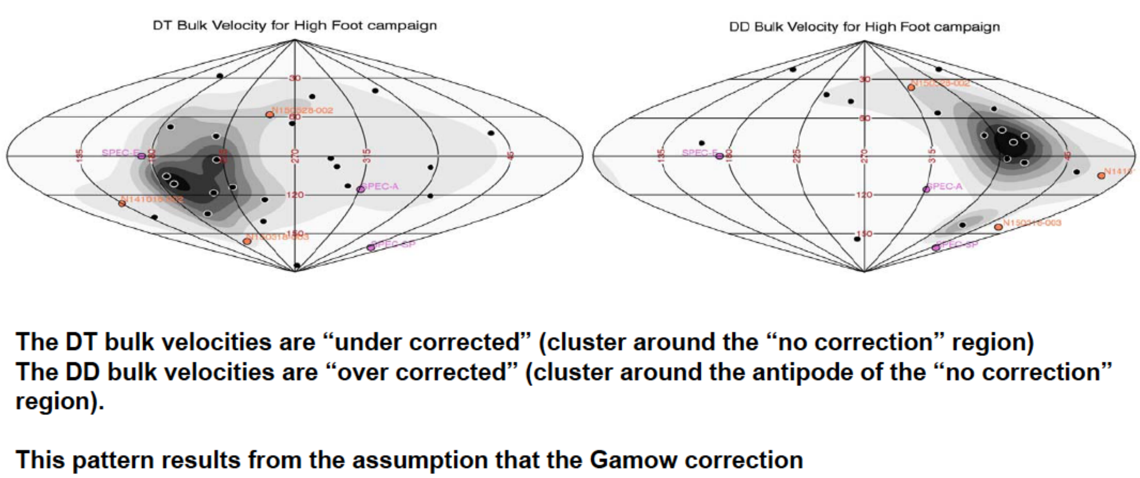


Figure 5: Evidence that $T_{ion}(DT)_{min}$ may not represent the true thermal temperature.

Moderators documentation

I General Session Summary

There were four talks given during this session. These talks were: "Temperature in high foot implosions: Tion is too high" given by Brian Spears; "HiFoot Tion and DT/DD yield ratios – what we know and do not know" given by Maria Gatu-Johnson; "Te measurement status" given by Prav Patel; and "High-Foot Workshop nToF Update" given by Gary Grim. The question that ties all of these presentations together is: "How do we determine a thermodynamic temperature for the hot-spot that can be used to determine a pressure?" This question is common to X-ray Drive and Direct Drive ICF implosions and the High-Foot experimental campaign has provided valuable data towards an answer. The second question suggested by the title of this session is: "Why is the measured DSR 70% - 80% of what is calculated from simulations?" Very little was said about DSR in this session despite the session's title. Data acquired is of high precision that detailed physical models can be compared to answer both questions. That being said, there is clearly an important measurement that has not been made. We do not know the temporal profile of the fusion burn. "Bang Time" and "Burn Width" measurements are insufficient.

I.a Temperature in high foot implosions: Tion is too high

More than just temperature is encoded in the width of the DT and DD neutron spectra. The simulation data presented clearly showed that implosions with large velocity distributions will have wider peaks. While this may be obvious, it does imply that a single temperature Maxwellian velocity distribution is incorrect and will not describe high quality neutron spectra data. The case was made that we need to be more sophisticated in our analyses. Measured ion temperatures exceed simulation results by several hundred eV, so something is missing from the simulations. The comparison of DT and DD spectra will help unravel the reasons for the discrepancy. There is still the question of why the Tion measurements do not show a larger spread in value. The sampling argument does make sense but then the question becomes how many are needed and where should the Tion measurements be made?

I.b HiFoot Tion and DT/DD yield ratios – what we know and do not know

The data shown do make a case for residual kinetic energy (ed. RKE) is encoded in the ion temperature analysis but the magnitude of it is still unknown (ed. because the fuel mass is generally over 20 times the hot-spot mass, RKE is most directly related to fuel motion so it's difficult to relate ion temperature of the hot-spot to RKE). The fact that measured T_{ion} is higher than simulated points to a larger velocity distribution than in the simulations. A simple calculation using the analysis by Brian Applebee and Tom Murphy give a thermal temperature that is too low to explain the measured yields. More data from imposed perturbations may help untangle this problem.

The DT to DD yield ratio is a different problem. While it may indicate that the T_{ion} measurement does not reflect the temperature used in the reactivity calculation, it more likely points to the lack of knowledge of the isotopic fraction in the DT layer. Data were shown that indicates that the yield ratio does track with the triple point temperature. If we think that there is information in the yield ratio important to determining a thermal temperature, then a better measure of the isotopic fraction is needed.

I.c Te measurement status

This was an update on the filter change planned for the Spider Streak Camera diagnostic from the current Ross Filter pairs to a series of Ti filters with different thicknesses. The rational presented for the change makes sense and should give the expected results if the signal-to-noise is adequate. The electron temperature measurement is important and may help with determination of the thermodynamic temperature. Sensitivity of the streak camera cathode will limit the highest energy x rays detectable. There is also the issue of Ti florescence creating a background and limiting the signal-to-noise. This effect was not adequately addressed in the discussions during the presentation and as such needs to be looked at. The current models for x-ray cathode response are applicable for x-ray energies less than 10 keV. It is not clear that the assumptions that went into these models are correct for higher energy x rays. Measuring the slope of the x-ray continuum to determine a temperature relies on either a calibration of the cathode response or a good model for the response.

I.d High-Foot Workshop nToF Update

Neutron time-of-flight (nToF) data from the High-Foot experiments is of high quality and unique in ICF. The high yields and areal densities approaching 1 g/cm^2 (ed. typical HF implosions have areal densities of ~0.8 g/cm^2) provide rich neutron spectra never before available. These facts allow the use of analysis techniques for nToF data far beyond what has been previously possible. This was a good summary of what has been done with the forward fitting using a Ballabio model for the emission spectrum and the planned analysis of the spectral moments. The description of the DT and DD "bulk" velocity analysis was confusing and it was not put in context with previous analysis, or if it was I missed this. The energy shift due to temperature in the Ballabio analysis is always positive. It is not clear if there is a temperature for which the two velocity vectors agree. The plot comparing the skew values from the DT and DD analysis was interesting that they agreed for the limited data set shown. If skew primarily depends of the temperature distribution and not velocity then you would expect these two to agree even if the second and fourth moments did not agree.

II Workshop Summary

The FDSR measurement was briefly discussed in other workshop sessions. An implication was made that preheating the cold fuel layer with hot electrons did not explain the difference. There was a back-up slide in Brian Spear's presentation that presented five hypotheses for this.

- Preheat
  - Hot electrons
  - Hard x-rays (Au M-band)
- Shock mistiming
- EOS uncertainty
- Low mode asymmetries
- High mode asymmetries

More discussion is needed on the DSR differences and how we can reconcile the difference with the other implosion data.

It is clear from the quality of the data presented during this workshop that the High-Foot experimental series has been a success. It has fulfilled the original goal of being an implosion platform that could separate the low-mode effects from the high-mode effects. Just because we now know when the High-Foot implosions break, it does not mean that they have served their purpose. This will be a very useful platform to study hohlraum coupling, to determine if controlling shape reduces residual kinetic energy, and testing hypotheses of how the hot-spot assembles. My least favorite of the proposed experiments is the two-shock implosions (ed. 2-shock CH implosions are an HED campaign that have demonstrated excellent symmetry control so far, but this implosion was not designed with ignition purposes in mind) and would suggest that if more shots are needed for other physics issues that these have the lowest priority.

An experiment that may shed light on the residual kinetic energy would be to impose a large P2 along the hohlraum axis (Spec SP and proposed Spec NP directions) and in a second shot along the equator (Spec E direction). Comparing the nToF data from these two shots will help understand the moment analysis of the DT and DD peaks.

Session #5

The fight for symmetry and reducing symmetry swings

Presenters: T. Ma, A. Pak & Moderator: J. Leidinger (CEA)

Summary:

- *Controlling symmetry in the high-foot implosion has been challenging.*

Key points from presentation

- Scalings of high-foot hot-spot shape with target and laser changes are well established and these scalings match the low-foot experience.
- Longer duration of peak power swings the stagnated hot-spot shape oblate.
- Higher laser power drives the stagnated hot-spot shape oblate.
- Brightness between the inner cone and outer cone beams, as measured by soft x-ray imaging (SXI), indicates 'late-time' asymmetry.
- Observed shapes are reasonably repeatable and consistent between nuclear and x-ray.
- Hot-spot shape swings are slightly larger for thinner ablators.
- Further improvement of high-foot hot-spot shape at stagnation is unlikely to yield much improvement.
- Reducing shape swings is likely to produce a significant improvement in yield.

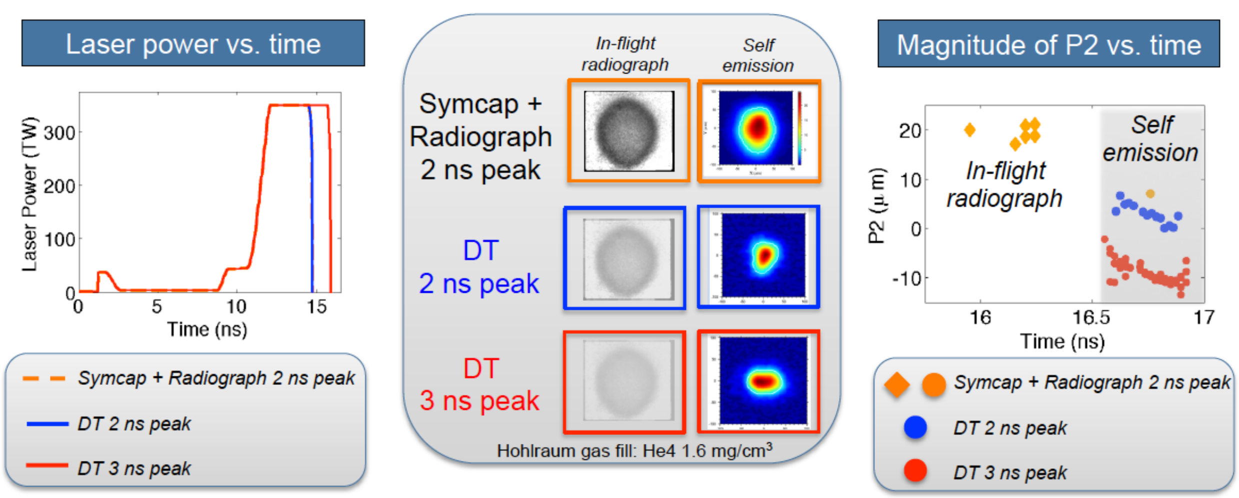


Figure 6: A P_2 asymmetry swing between the shape of the shell at peak velocity and the shape of the x-ray self-emission at stagnation is observed and an offset is seen with an extended duration of peak power (reduced coast-time).

Moderators documentation

<u>Art Pak</u>

We mainly look at Re-emit, VISAR, 2DConA, and hot-spot self-emission (and starting to look at SXI).

We don't incorporate rhor asymmetry measurements at shock bangtime from wedge-range filters, but we should.

We observed empirical trends in hot spot P2 vs. laser power.

Extending laser pulse (keeping everything else constant) drove implosion oblate (130501, 130812). Why? Was it just late time asymmetry or reversal of early time asymmetry?

At what point does the capsule not care what the hohlraum is doing? We saw response down to 400 ps. Valeri - It should be that when hot spot pressure exceeds ablation pressure. Omar - that happens late in time (ed. past the time of peak velocity). Even after this point the outside pressure still tamps the shell so still makes a difference.

Re-emission showed we were putting higher flux on waist (-10% P2). Implies 15% drive asymmetry. Jim - how sure are you that you are correcting for the patch properly? Art - we use viewfactor calculations, we think it's good enough. JP - the 5% diff you have between exp and sim is seen in rugby too.

Is the toe optimum? We think so. (ed. we tried one solution and it worked to address picket hot electrons, but a deeper study of other choices was not ever performed.)

To fix the picket CF we would have introduced hot electrons.

VISAR S1 breakout shows still negative P2 flux but half of before (7.5%). S1-S2 merger times are same so there must be a reversal in asymmetry.

HF loses VISAR trace before LF. Probably due to hot electrons (ed. recent work in 2016 with the HF in low gas-fill hohlraums appear to confirm this since the low gas-fill hohlraums don't blank VISAR). We lose pole mirror before equator.

2D ConA shows +20um P2. Self emission ~10um and swings negative over burn, so there is a negative swing between end of ConA and bangtime. When we extend the pulse we see the same negative swing but it's even more negative.

Return shock will affect symmetry (reverse asymmetry). We should look at this more (Ryan's simulations, can we measure it?).

SXI - simulation predicts continuous inner cone band, but experiments do not show continuous band. Jim - surprised that signal is linear with deposited laser power. Laurent - that's what simulations showed in the cone fraction scattering plate experiments.

SXI analysis suggests that between 2 to 3 ns the outer cone gets brigher but the inner doesn't. Steve - could be because your linear assumption isn't right? Need to check.

SXI - where does the rest of the inner cone go? Is it CBET shutting down, or inner beam propagation problem? Various things we could do to investigate these hypotheses...

We know we have early time asymmetries driving waist-high. Late time we are driving pole high.

DU improved P2. We didn't do a DU ConA to check that in-flight P2 also got better.

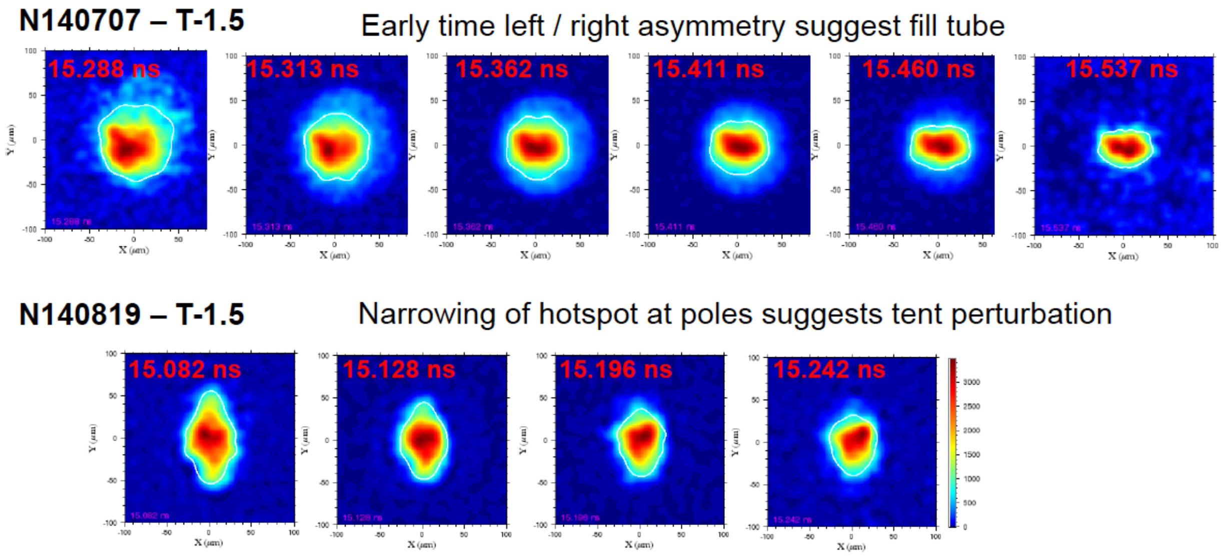


Figure 7: As the ablator is thinned, engineering feature effects on the capsule become more apparent.

Tammy Ma

P2 amplitude and swing changes with ablator thickness. Thinner ablator reduces negative P2. Thinner ablators started out more positive P2 but then have larger negative swing.

As ablator is thinned capsule effects become more apparent (tent and fill tube). We sometimes see a fill tube jet move across the hot spot. And something that looks a lot like the tent.

HF tent feature is seen in 2ConA reconstruction.

+700 hohlraum fixed P4 in flight. We saw a similar P2 swing. P2 absolute is zero in-flight but then oblate at bangtime. We're not sure exactly what's going on with early time swings. JP - rugby sees same thing.

+700 hohlraum produced terrible shape that we did not think we could quickly fix.

When we have intentional known large asymmetries we do see shape is affected and degradation in yield (ice M1, bundle misfire, drive P1). However, an intentional ice P1 experiment just had a small degradation in yield (maybe about what was predicted - simulations didn't predict much degradation but we weren't sure we could believe them).

Repeats of 140520 showed pretty repeatable shape in both x-ray and nuclear. FNADs also pretty repeatable.

Izumi compares self-consistency of 3D x-ray reconstruction with NIS. They are pretty consistent for a wide range of shots.

Debbie's model suggests that our sensitivity to (ed. hot-spot) P2 is quite low (20%) - velocity changes are dominant. Valeri - you can use simulations to look at yield sensitivity to P2 and P4 (Annie's dataset).

From Annie's simulations just improving P2 and P4 at bangtime doesn't help that much - still a lot of RKE due to asymmetry throughout the pulse. We'd really need to reduce asymmetry thoughout the pulse.

Session #6

Path Forward

Presenters: D. Callahan & Moderator: P. Gauthier (CEA)

Summary:

- *The plan forward focuses on intermediate gas-fill hohlraums (0.3-0.6 mg/cc He) that have already demonstrated low LPI and low hot electron levels.*

Key points from presentation

- Intermediate gas-fill hohlraum have drive multipliers closer to 1 than high-gas fill hohlraums.
- Symmetry trends in intermediate gas-fill hohlraums are closer to simulation expectations (but offsets still remain).
- Experiments of gas-fill indicated that SRS and drive multipliers kick-in above 0.6 mg/cc.
- Hot electron levels are measured to have dropped by 100x when moving from the high gas-fill high-foot hohlraum to the low gas-fill one for an equivalent radiation temperature drive history.
- The P4 asymmetry present in the high gas-fill high-foot hohlraum has been reduced by 3x.
- 1^{st} 672 intermediate fill hohlraum high-foot showed marked improvement in stagnation pressure and yield, for the implosion speed.
- Getting the inner beams to the waist of the hohlraum remains challenging.

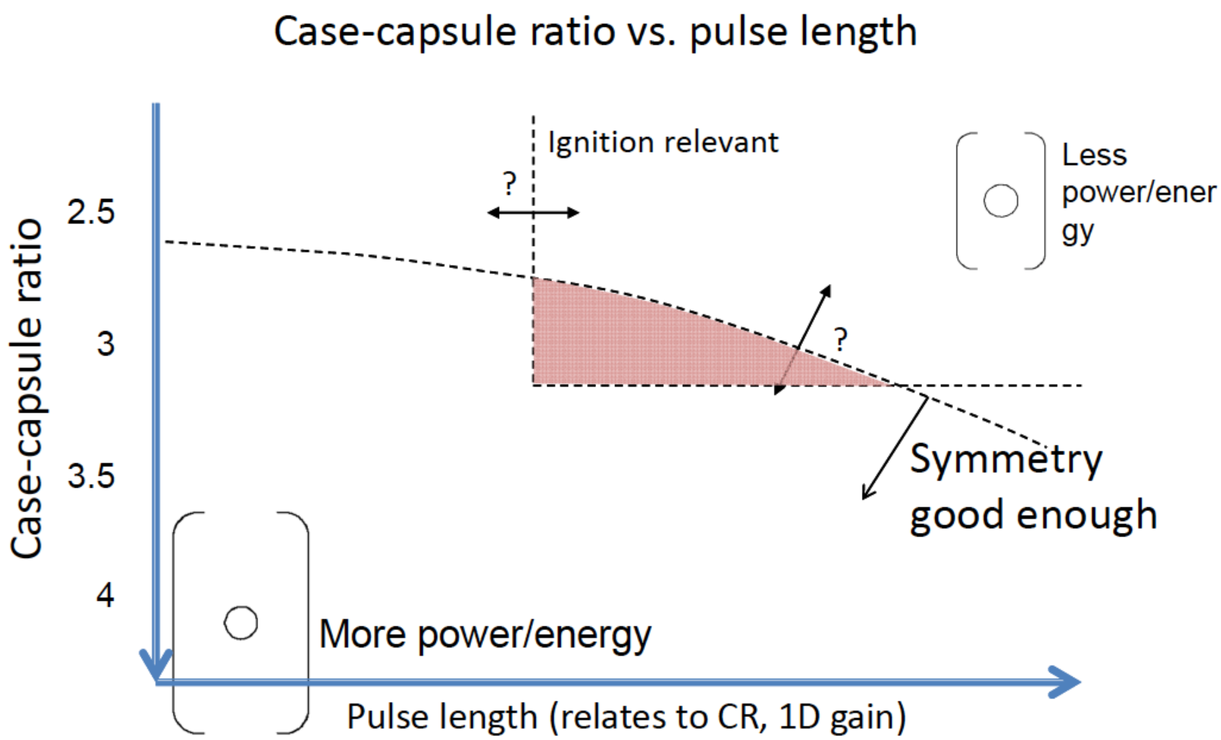


Figure 8: Can we find designs with "good enough symmetry" inside NIF's energy envelope?

Moderators documentation

During the session, Debbie Callahan gave a detailed talk on the path forward for integrated implosions and hohlraums.

It was first pointed out that NIF scale ICF hohlraums fall roughly into two categories: high gas fill, LPI dominated hohlraums and low gas fill, rad-hydro dominated holhraums. High gas fill hohlraums show a low coupling and a strong time dependent drive asymmetry. Low gas fill hohlraums show a higher coupling, lower hot electrons and a better symmetry. They also turn out to be more predictable: across HDC and CH ablators at 3.1-4.25 case-to-capsule ratio (CCR), rise and peak multipliers used in LLNL hydro-rad simulations are ~0.85-0.9 in low gas fill hohlraums compared to 0.5-0.75 in high gas fill hohlraums.

It was emphasized next that the degraded propagation of the inner beams observed in most experiments motivated the use of larger hohlraums and shorter pulses, new design ideas, while in parallel attempting to understand the complicated physics of this from focused experiments. A larger hohlraum has thus been tested on NIF (so called "672" due to its 6.72 mm diameter; former hohlraum design had a 5.75 mm diameter) showing improvement in P4 and hot electrons, more conformal shell and hot spot, better propagation of the inners and improvement in pressure and yield for a given coast time and laser energy. However, in a subsequent shot using the 672 hohlraum where coast time has been reduced, lost control of P2 was observed. In FY17, CCR will be increased to regain P2 symmetry control.

The LLNL "base camp" strategy for hohlraums was finally presented. Goals are to understand the safe operating space for the hohlraum and to find designs with good enough symmetry inside NIF's envelope, varying the CCR, pulse length and capsule designs. LLNL have a draft set of requirement drive asymmetry. At the requirement, drive asymmetry is expected to give > 70% YOC in 2x alpha heating regime based on simulations. Existing HDC, CH and Be designs give diversity in spanning hohlraum and capsule stability risk. Two designs (HDC subscale and CH "2shock") either meet or are close to meeting the drive symmetry requirements.

To summarize, LLNL plan for the upcoming years is to focus on low LPI rad-hydro dominated hohlraums with goal of round implosion. It is proposed to put most of the effort into understanding these hohlraums rather than trying to understand high fill, high LPI hohraums. In parallel, other methods for holding the capsule and measuring impact of tent and fill tube will be explored, since these engeenering features have been demonstrated to significantly degrade the implosion symmetry.

During the discussion that accompanied the presentation, the following issues were addressed:

LLNL clarified that E2/T2 hot electrons come from forward stimulated Raman scattering or two-plasma decay. But it is not clear where the highest energy electrons (>170 keV) come from.

It was argued that the fact that multiplier in peak is closer to 1 for 672 high-foot low gas-fill design is not pulse length effect since similar pulse length as 575 high-foot was used, but could also be due to larger hohlraum, not lower gas-fill. However, LLNL never did high gas-fill 672 to check this hypothesis.

LLNL near-vacuum hohlraum and 0.3 mg/cc gas-fill simulations for CCR = 4.25 2-shock implosions predict less equator drive. CEA simulations reproduce symmetry.

LLNL runs Particle-In-Cell simulations to model recent Omega counter-propagating plasmas experiments, and to understand when kinetic effects matter in hohlraums. This work could end up in the building of a reduced model in Hydra to better account for plasma collision and interpenetration.

Symmetry in picket and trough requirements are needed. The 70%YOC symmetry requirements are based on NIC low-foot simulations. It should be verified that they also apply to higher adiadat HDC and Be designs (or too stringent). There is a need to understand why requirements don’t seem to depend on convergence ratio in simulations between say adiabat 3 and adiabat 1.5 implosions. What would be expected analytically?

Fill tube goes deeper in sub scale HDC, besides being larger fraction of surface area, so worse effects are expected. Meteors don’t seem correlated with dust based on latest shots.

There is the concern that the subscale platform be a good hohlraum surrogate (because of LPI). LLNL points out that the scaling is probably better in the low LPI regime of the present and future NIF shots. It has been also suggested during the discussion to put smaller phase-plates on some beams at sub-scale to match intensity.

Editors end-note

"The 'High-Foot' platform manipulates the laser pulse-shape coming from the National Ignition Facility laser to create an indirect drive 3-shock implosion that is significantly more robust against instability growth involving the ablator and also modestly reduces implosion convergence ratio. This strategy gives up on theoretical high-gain in an inertial confinement fusion implosion in order to obtain better control of the implosion and bring experimental performance in-line with calculated performance, yet keeps the absolute capsule performance relatively high."

> *-- Part of abstract of 1st Invited APS Division of Plasma Physics paper (Paper QI3 4, Bull. Am. Phys. Soc., 58, 279, 2013) on the High-foot Implosion. Abstract submitted one month after the 1st High-foot DT implosion, N130501. Also see Phys. Plasmas*, **21**, 056314 (2014).

The original goal of the high-foot was not to jump directly to ignition, but instead, in today's language, to establish a "basecamp" that had a chance of behaving in a way that is consistent with our predictive capability. The purpose of having a basecamp is that it can be used to reach towards higher performance in a series of stepwise extrapolations from a starting point that is understood and calculable. This approach has taken time and discipline, not the least because judicious choices of step-sizes were not know aforehand. In combination with more focused experiments, this approach has allowed clear hypothesis to be developed as to significant obstacles to further increasing performance.

We would like to thank the high-foot team, the ICF/HED Programs, and the NIF for the success of the high-foot implosion campaign. We would also like to thank all the Workshop participants and speakers for their efforts to make the Workshop successful.

- Omar A. Hurricane
- Debbie A. Callahan
- Pravesh Patel

Appendix A – High gas-fill 575 hohlraum high-foot shot list

N-number	Type	Ablator	Hohlraum	Notes
121023	Keyhole	T0 (195 um)	5.75 Au	
121102	Keyhole	T0	5.75 Au	
121103	Symcap	T0	5.75 Au	Official beginning of High-foot experiments
130108	Symcap	T0	5.75 Au	
130122	Keyhole	T0	5.75 Au	
130214	Keyhole	T0	5.75 Au	Correction for picket hot-electrons
130303	2DConA	T0	5.75 Au	
130409	1DConA	T0	5.75 Au	
130501	DT	T0	5.75 Au	Mini-quench as are almost all HF DT's
130508	2DConA	T0	+700 Au	
130521	Keyhole	T0	+700 Au	Excellent shock symmetry
130522	Re-emit	N/A	+700 Au	
130530	DT	T0	5.75 Au	bad m=1 in layer, yield half of N130501
130710	DT	T0	5.75 Au	1^{st} DT > 1e15 yield, but toroidal shape
130726	Keyhole	T0	+700 Au	
130730	2DConA	T0	+700 Au	Still oblate. P2 not responding to changes.
130802	DT	T0	+700 Au	Poor results. Decision to abandon +700 made.
130808	2DConA	T0	+700 Au	Confirms that P2 not controllable in +700
130812	DT	T0	5.75 Au	1^{st} significant alpha heating with 'no-coast'
130927	DT	T0	5.75 Au	Reduced coast, more CBET, 3 color change
131118	2DConA	T-1 (175)	5.75 Au	Symmetry improves
131119	DT	T0	5.75 Au	Reduced coast, more CBET, max NIF energy
131126	Keyhole	T-1	5.75 Au	
131219	DT	T-1	5.75 Au	Uncertain about morphology of cryo layer
140120	DT	T0	5.75 DU	9.3e15, improved symmetry, 1.88 MJ!
140124	Keyhole	T-1	5.75 Au	
140225	DT	T-1	5.75 Au	Record bad ice layer, but repeats 131219
140227	Re-emit	N/A	5.75 Au	Picket is found waist-hot at CF = 5.8%
140304	DT	T0	5.75 DU	High power version of N140120
140311	DT	T-1	5.75 Au	
140430	Re-emit	N/A	5.75 Au	
140501	2DConA	T-1.5	5.75 Au	Symmetry improves
140511	DT	T0	5.75 Au	Test of full-quench DT layer (higher C.R.)
140520	DT	T-1	5.75 DU	Highest inferred stagnation pressure ~ 230 Gb
140526	Keyhole	T-1.5	5.75 Au	

140601	1DConA	T-1	5.75 Au	Dropped quad, energy 8% low
140707	DT	T-1.5	5.75 Au	
140819	DT	T-1.5	5.75 DU	Fabricated capsule buckled by UV damage
140822	Keyhole	T-1	Rugby/Au	CEA collaboration
141008	DT	T0	5.75 DU	Reduced 2nd shock strength
141016	DT	T-1	5.75 DU	Repeat of N140520/Bundle misfire
141102	Keyhole	T-1	Rugby/Au	
141106	DT	T-1	5.75 Au	Repeat of N140255
141111	2DConA	T0	5.75 DU	3 shock adiabat shaping
150104	Re-emit	N/A	Rugby/Au	
150115	DT	T0	5.75 DU	3 shock adiabat shaping
150121	DT	T-1	5.75 DU	Repeat of N140520 and did.
150126	2DConA	T-1	Rugby/Au	
150211	DT	T-1.5	5.75 DU	Back-off of coast-time from N140819
150218	DT	T-1	5.75 DU	Push N140520 over “cliff”
150318	DT	T-1	5.75 DU	Intentional P1 study (Stagnation Campaign)
150329	2DConA	T-1	Rugby/Au	
150401	DT	T-1.5	5.75 DU	Slight CF change, effective repeat of 150211
150409	DT	T-1	5.75 DU	Repeat of N140520 with “young fuel”
150416	DT	T-1	5.75 DU	3 shock adiabat shaping
150504	2DConA	T-1	Rugby/Au	3 color test
150512	1DConA	T-1	5.75 Au	Get velocity of best DT, but DU target broke
150518	DT	T-1	5.75 DU	Intentional P2 study (Stagnation Campaign)
150528	DT	T-1	5.75 DU	Intentional ice P1 study (Stagnation)
150531	Keyhole	T-1	672 DU	1st low gas-fill hohlraum for CH
150610*	DT	T0	5.75 DU	DU shape corrected version of 130812

* Last high gas-fill high-foot *campaign* experiment.

Appendix B – High-foot Implosion References

Dittrich, T. R., et al. Design of a High-foot/High-Adiabat ICF Capsule for the National Ignition Facility, *Phys. Rev. Lett*., **112**, 055002 (2014).

Park, H.-S., et al. High-adiabat, high-foot, inertial confinement fusion implosion experiments on the National Ignition Facility, *Phys. Rev. Lett*., **112**, 055001 (2014).

Hurricane, O.A., et al., Fuel gain exceeding unity in an inertially confined fusion implosion, Nature, 506, 343-348, (2014). doi:10.1038/nature13008. Op cit. doi:10.1038/nature13533.

Hurricane, O.A., et al. The high-foot implosion campaign on the National Ignition Facility, *Phys. Plasmas*, **21**, 056314 (2014).

Raman, K.S., et al. An in-flight radiography platform to measure hydrodynamic instability growth in inertial confinement fusion capsules at the National Ignition Facility, *Phys. Plasmas*, **21**, 072710 (2014).

Casey, D.T., et al. Reduced instability growth with high-adiabat high-foot implosions at the National Ignition Facility, *Phys. Rev. E*, **90**, 011102 (2014).

Ma, T., et al. Thin-shell high-velocity ICF implosions on the National Ignition Facility, *Phys. Rev. Lett*., **114**, 145004 (2015).

Doeppner, T., et al., Demonstration of High Performance in Layered Deuterium-Tritium Capsule Implosions in Uranium Hohlraums at the National Ignition Facility, *Phys. Rev. Lett*., **115**, 055001 (2015).

Callahan, D., et al., Higher velocity High-foot implosions on the National Ignition Facility, *Phys. Plasmas*, **22**, 056314 (2015).

Betti, R., et al., Alpha Heating and Burning Plasmas in Inertial Confinement Fusion, *Phys. Rev. Lett*., **114**, 255003 (2015).

Nagel, S.R., et al. Effect of the mounting membrane on shape in inertial confinement fusion implosions, *Phys. Plasmas*, **22**, 022704 (2015).

Tommasini, R. et al. Tent-induced perturbations on areal density of implosions at the National Ignition Facility, *Phys. Plasmas*, **22**, 32309 (2015).

Kritcher, A., et al. Integrated modeling of cryogenic layered High-foot Experiments at the NIF, *Phys. Plasmas*, accepted, (2016).

Clark, D.S. et al. Three-dimensional simulations of low foot and high foot implosion experiments on the National Ignition Facility, *Phys. Plasmas*, **23**, 056302, (2016).

Dewald, E.L., et al. Generation and beaming of early hot electrons onto the capsule in laser driven ignition hohlraums, *Phys. Rev. Lett*., **116**, 075003, (2016).

Hurricane, O.A, et al., Inertially confined fusion plasmas dominated by alpha-particle self-heating, *Nature Phys*., DOI:10.1038/NPHYS3720 (2016).

Appendix C – Workshop Participants

LLNL External Participants:

Bahukutumbi, Radha – LLE	rbah@lle.rochester.edu
Batha, Steve – LANL	sbatha@lanl.gov
Beg, Farhat – UCSD	fbeg@ucsd.edu
Campbell, Mike – LLE	mcamp@lle.rochester.edu
Chittenden, Jeremy – Imperial, UK	j.chittenden@imperial.ac.uk
Falcone, Roger – Berkeley	rwf@berkeley.edu
Frazier, Njema – NNSA, HQ	Njema.Frazier@nnsa.doe.gov
Frenje, Johan – MIT	jfrenje@psfc.mit.edu
Gauthier, Pascal – CEA	pascal.gauthier@cea.fr
Goncharov, Valeri – LLE	vgon@lle.rochester.edu
Haynes, Don – LANL	dhaynes@lanl.gov
Johnson, Maria Gatu – MIT	gatujohnson1@llnl.gov; gatu@psfc.mit.edu
Kline, John – LANL	jkline@lanl.gov
Knauer, Jim – LLE	jkna@lle.rochester.edu
Leeper, Ray – LANL	rleeper@lanl.gov
Leidinger, Jean-Pierre – CEA	jean-pierre.leidinger@cea.fr
McGlinchey, Kristopher – Imperial, UK	k.mcglinchey13@imperial.ac.uk
Olson, Rick – LANL	reolson@lanl.gov
Peterson, Kyle – Sandia	kpeters@sandia.gov
Sangster, Craig – LLE	csan@lle.rochester.edu
Tsung, Frank – UCLA	tsung@physics.ucla.edu
Woolsey, Nigel – York, UK	nigel.woolsey@york.ac.uk

LLNL Internal Participants (does not include walk-ins, but should if anyone remembers…):

Bradley, David	bradley9@llnl.gov
Callahan, Debbie	callahan1@llnl.gov
Casey, Dan	casey21@llnl.gov
Cerjan, Charlie	cerjan1@llnl.gov
Clark, Daniel	clark90@llnl.gov
Dittrich, Tom	dittrich1@llnl.gov
Doeppner, Tilo	doeppner1@llnl.gov
Edwards, M. John	edwards39@llnl.gov
Gaffney, Jim	gaffney3@llnl.gov
Grim, Gary	grim3@llnl.gov
Jarrott, Charlie	jarrott1@llnl.gov
Kritcher, Annie	kritcher2@llnl.gov

Haan, Steven	haan1@llnl.gov
Herrmann, Mark	herrmann9@llnl.gov
Hinkel, Denise	hinkel1@llnl.gov
Hurricane, Omar	hurricane1@llnl.gov
Kilkenny, Joseph	kilkenny1@llnl.gov
Ma, Tammy	ma8@llnl.gov
Maclaren, Steve	maclaren2@llnl.gov
MacPhee, Andrew	macphee2@llnl.gov
Mariscal, Derek	mariscal2@llnl.gov
Milovich, Jose	milovich1@llnl.gov
Pak, Art	pak5@llnl.gov
Park, Hye-sook	park1@llnl.gov
Patel, Pravesh	patel9@llnl.gov
Robey, Harry	robey1@llnl.gov
Salmonson, Jay	salmonson1@llnl.gov
Spears, Brian	spears9@llnl.gov
Town, Richard	town2@llnl.gov
Turnbull, David	turnbull2@llnl.gov