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The high-foot implosion campaign on the National Ignition Facility

O. A. Hurricane

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If you could identify only one key skill that a primary or secondary designer should posses, it would be the ability to design an implosion that works reliably and as advertised. Being able to harness an implosion is a key skill because of what an implosion does – an implosion is a "pressure amplifier" that takes absorbed energy and turns that energy, with significant energy loss, into pressure. The pressure generated in implosions is used to compress materials to high densities in the primary designers case, and high densities and temperatures in the secondary designers case. While primary designers and their simulation tools can be tested against experiments at scale fielded at high-explosive facilities around the NNSA complex, secondary designers are much more limited in the experimental facilities that can access relevant conditions (facilities such as Omega at the Laboratory for Laser Energetics, the Z-machine at Sandia National Lab in Albuquerque and the National Ignition Facility at Livermore are more-or-less it). Ignition conditions are the highest-pressure and therefore hardest conditions to access with facility levels of energy, but the struggle to obtain ignition has been an illuminating test of the stockpile stewardship model.

If you thought the criteria for ignition is when the fusion energy output from an inertially confined fusion (ICF) implosion exceeds the energy delivered to the target, you'd be wrong. While the above definition is used for milestone tracking purposes, the actually definition of ignition that has been used in fusion research since 1957 is when the power produced by the fusing region exceeds the rate at which energy is lost from the fusing region due to x-ray radiation processes and heat conduction processes. This simple statement about fusion power and rates of energy loss lead to a quantitative criterion for ignition that is known as the "Lawson Criteria." [1,2]

The Lawson criteria is a statement that relates the plasma pressure, P, and plasma confinement time, τ, to a criteria that defines ignition. In its simplest form the Lawson criteria for ignition of deuterium-tritium (DT) fusion fuel is, $P\,\tau > 30$ atm-s (atmospheres x seconds) although the exact number can vary somewhat (but not too greatly) depending upon plasma density and temperature. The Lawson criterion suggests why obtaining ignition is so challenging. For modest plasma pressures of atmospheres, the plasma confinement time must be many 10's of seconds (the magnetic fusion case). For small confinement times of less than a nanosecond, the plasma pressures must be enormous and on the order of many hundreds of billions of atmospheres (the inertial confinement fusion case).

Achieving high pressures in an ICF implosion requires finessed control over implosion shape, DT fuel compressibility (adiabat), while at the same time obtaining very high implosion velocities (several hundreds of kilometers per second). Obtaining high implosion velocities risks introducing instabilities that can tear apart and implosion and those instabilities can generate mix that can be quite damaging to an implosion.

While not the only problem with the National Ignition Campaign (NIC) point design implosion (the “low-foot” implosion), it appears that ablator-DT mix was a major contributor to it not performing as desired for the higher velocity NIC implosions [3-5]. Recently, a “high-foot” implosion [6-8] has been developed with the specific goals of testing a high-performance implosion that is more robust against ablation-front Rayleigh-Taylor (A-RT) instability [9], has less convergence, and is generally less sensitive to modeling uncertainties. The modeling and assertions of less instability growth with the high-foot pulse-shape were directly tested and verified in radiography experiments [10,11] while the integrated implosions themselves continue to express no indications of mix as inferred from hot-spot emission measurements [12].

While this “high-foot” implosion scales back from the goal of high gain ignition by giving up some potential compression of the DT fuel, its performance has greatly exceeded past implosion performance as demonstrated by recent implosions obtaining “fuel gain” (where the fusion yield exceeds the energy delivered to the fusion fuel), more that a yield doubling due to alpha-particle self-heating and the highest levels of Lawson criteria to date (see Figure 1).

The datum shown in the upper right hand side of Figure 1 show that much progress towards ignition has been made, but the points also belie the challenges that remain in order to push further towards the ignition regime. While high performing, most high-foot implosions exhibit hot-spots (the DT yield producing region in a non-igniting ICF implosion) that are oblate in shape and can even verge on toroidal (Figure 2). This “low-mode” shape control problem becomes worse as the laser power and to a lesser extent laser energy are increased. However, an increase in laser power is the easiest way to access higher implosion speeds and remember higher implosion speeds are how an ICF implosion’s fusion performance is most directly increased. An alternate way to increase implosion speed with a given laser power and energy is to use a more efficient ablator like high-density carbon (HDC) and work along these lines in presently going forwards [13,14].

Another avenue to higher fusion performance in the high-foot is to back off somewhat on the DT fuel stiffness (adiabat) generated by the strength of the high-foot’s first shock -- the trade-off that was made to obtain the improved high-foot stability. This “medium-foot” or “adiabat shaping” tactic seeks an optimum between the low-foot NIC implosion and the high-foot implosion, but it will be a matter of research to see if a tolerable amount of A-RT instability with higher DT fuel compressions can actually be achieved on the NIF.

With the benefit of a working and repeatable implosion, effectively the high-foot is a “base camp” from which we strike out in different directions in parameter space with and explore. The desire is to *evolve* the high-foot design as we press it to higher performance. In doing so, we will inevitably explore failure cliffs that test our designer judgment and the veracity of our simulation predictions – this is a key experience for those entrusted with the stewardship mission especially for the generation without any underground test experience.

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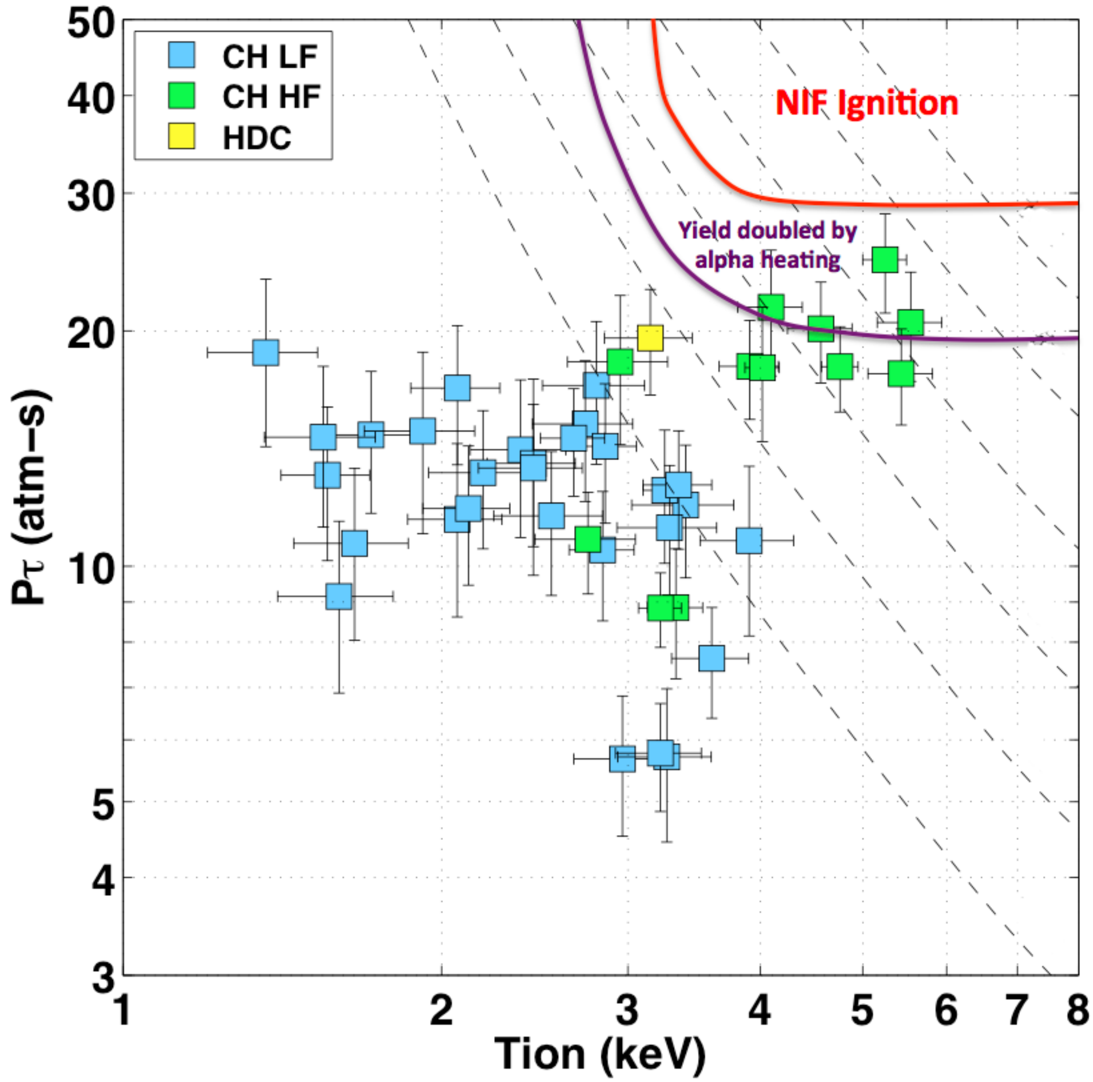

Figure 1. Lawson criteria (DT plasma pressure x confinement time in atmospheres x seconds) is plotted against inferred DT ion temperature (in kiloelectron volts). The datum are DT experiments NIF for low-foot NIC implosions (CH LF, in blue), high-foot implosions (CH HF, in green), and high-density carbon 2-shock implosion (HDC, in yellow). Contours of NIF ignition (red) and yield doubling due to alpha-heating (purple) are shown in the upper right hand corner. (Data plot courtesy of P. Patel of LLNL; alpha-heating and ignition contours courtesy of J. Hammer of LLNL).

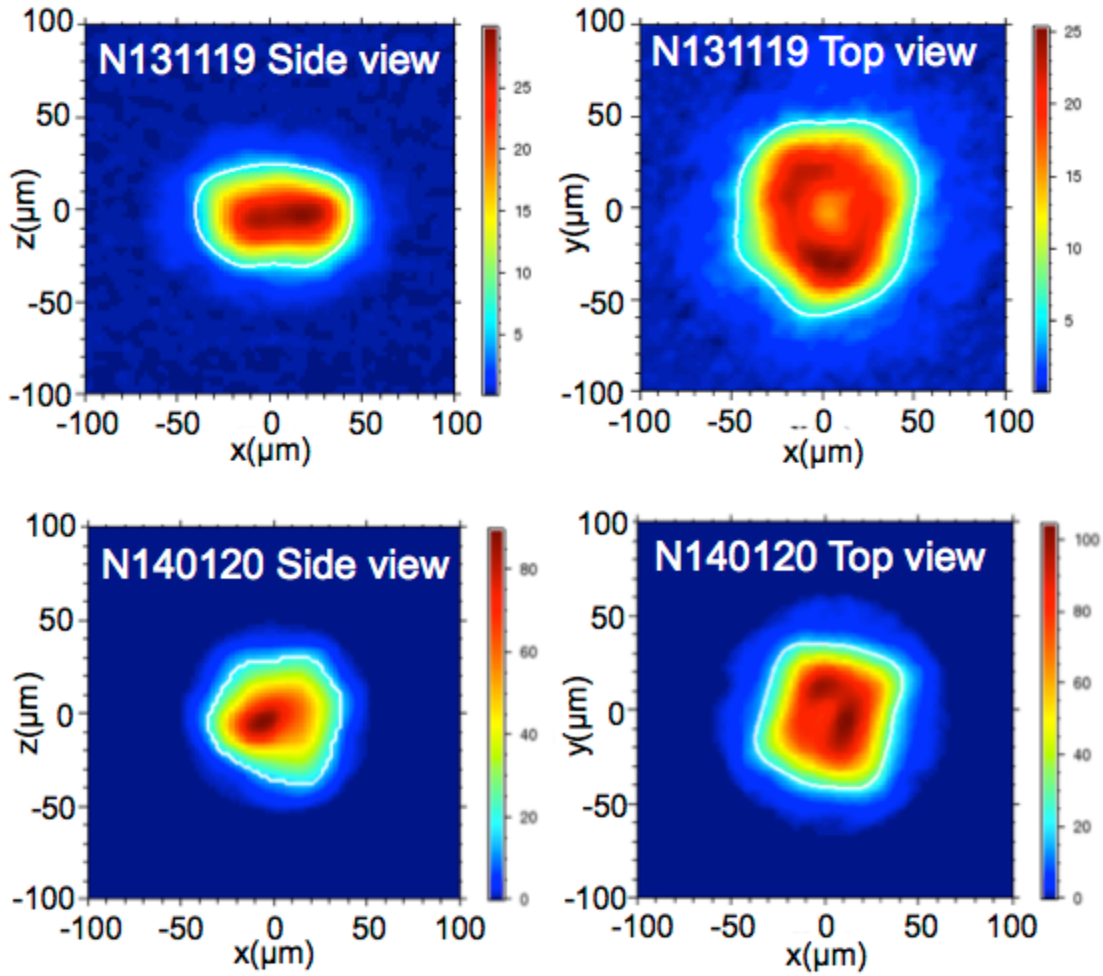

Figure 2. Hot-spot shape for two high performing high-foot implosions is shown in time-integrated x-ray imaging. Image spatial units are in microns. Shot N131119 (NIF year-month-day format NYYMMDD) was the highest performing DT shot in a gold hohlraum obtaining total DT yield of 6.1e15 neutrons while shot N140120 was designed to have the same implosion speed and bang-time of N131119 but was performed in a depleted-uranium hohlraum isolating the effect of improved shape. N140120 obtained a total DT yield of 9.3e15 neutrons. The shape of N131119 was characteristic of many of the high energy high-foot shots. Clearly, the depleted-uranium hohlraum was effective at improving the hot-spot shape. (X-ray image analysis [15] courtesy of N. Izumi, S. Khan, T. Ma, A. Pak, L.R. Benedetti, R. Town, and D. Bradley of the NIF Shape working group.)