

Science and code validation program to secure ignition on LMJ

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Abstract. The CEA/DAM ICF experimental program is currently conducted on LIL and Omega with the goal of improving our simulation tool, the FCI2 code. In this effort, we focus on typical ICF observables: hohlraum radiation drive history, capsule core shape and neutron emission history, hydrodynamic instability growth. In addition to integrated experiment, specific designs are also helpful to pinpoint a particular phenomenon. In this article, we review our current efforts and status, and our future projects on Omega and LMJ.

1. Introduction

The current baseline target for ignition on LMJ [1] features a Ge-doped CH capsule placed in a rugby shaped hohlraum [2], the latter being illuminated by 160 laser beams placed along two cones per hohlraum half, with 40 beams (10 quads) per cone. The results obtained during the National Ignition Campaign on the NIF pose several challenges to our understanding of hohlraum and capsule physics at the MJ laser energy level. Prominent among these are the reported drive deficit resulting in unexpectedly low peak capsule velocity [3], and exacerbated mix amounts in the DT hot spot [4]. Despite subtle differences in laser and target design for the LMJ and the French ignition program, it is likely that the failure modes reported on NIF could also stand in the way of ignition on LMJ. These results therefore prompt us to evolve our modelling capabilities in order to be able to better understand the NIC campaign finding, and provide a safer basis for design optimization for LMJ.

Integrated ICF target simulations show various sensitivities to a number of physical or numerical options, ranging from the choice of specific equations of state or opacities for the target material, to electron conduction or non-LTE atomic physics models, or target meshing choices. To prevent fallacious agreement between experimental results and post-shot simulations by *ad hoc* modelling choices, we try to identify a *single* optimal set of code and physical parameters that

- maximizes post-shot agreement
- gives robust simulation results in a reasonable computation time
- is grounded on the best physical model available

The final choice, and its abilities to operate predictively, depends of course on the diversity of the experimental database on which the modelling is tested. While past settings were solely based on Omega and LIL results, our current effort is to expand our database to NIF results, effectively asking for a model working point that is as relevant at 30 kJ as at 1.8 MJ laser energy.

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Integrated ICF experiments such as those carried out during the NIC campaign are efficient at identifying the existence of shortcomings in the modelling, but are not best suited to solve these puzzles, since so many physical phenomena are entangled in these experiments. Using LIL and Omega, we therefore strive to carry out experiments that help isolate specific physics problems in order to progressively validate our models piece by piece.

2. Radiation drive

Our workhorse code for integrated radiation hydrodynamics simulations is FCI2, a 2D lagrangian code including B-field generation and nonlocal electron conduction, and modeling NLTE effects in high-Z materials with the GonRad effective model. With those physics models and other numerical options, this code has been benchmarked against ~ 30 experiments in which the x-ray flux emitted from a laser-irradiated target was measured using broadband spectrometers such as Dante and DMX. These experiments range from open gas-filled or empty hohlraums on LIL, possibly featuring shields, gas-filled or empty hohlraums on Omega and NIF. The peak thermal radiation flux (in the 0-2 keV range) is always well modelled, within or very close to the error bars of the measurement. Agreement on the M-band flux, on the other hand, shows more variability.

In addition to the x-ray fluxes, LPI measurements (SRS and SBS spectra) are progressively included among the observables we consider, since they reflect the plasma dynamics inside the hohlraum and bring about additional criteria to judge the quality of the modeling. As an example, figure 1 illustrates a Stimulated Raman Scattering spectrum measured on Omega in a methane-filled rugby-shaped hohlraum, for which the typical “ μ -shaped” structure is well accounted for by the linear gain calculation with the Piranah LPI post-processor. This structure can be linked to backscattering from the denser gas region compressed between the expanding ablator and wall materials, close to the target equator (region (2) in figure 1(c)), whereas the fainter, broader and earlier structure originates from regions closer to the laser entrance hole (region (1) in figure 1(c)). However, this modelling can also sometimes be proved wrong, even for relatively small variations with respect to the present experiment, such as a slightly lower fill gas pressure.

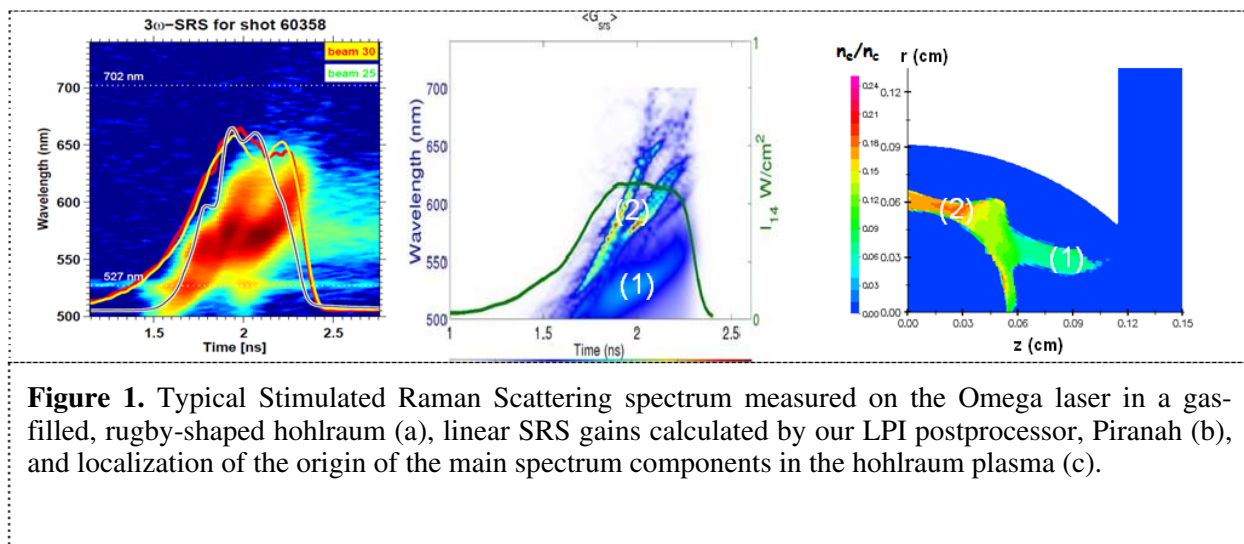


Figure 1. Typical Stimulated Raman Scattering spectrum measured on the Omega laser in a gas-filled, rugby-shaped hohlraum (a), linear SRS gains calculated by our LPI postprocessor, Piranah (b), and localization of the origin of the main spectrum components in the hohlraum plasma (c).

Measurements obtained on integrated ICF experiments – with their complex hydrodynamics and limited view of the gold emission regions – can be usefully complemented by specific, simplified experiments such as the one we carried out on Omega in June 2013 using gold-coated spheres. This campaign was a continuation of 2006 experiments for which the Dante and DMX broadband spectrometers would give conflicting measurements at high irradiance. Our latest measurements now support the highest conversion efficiency from the 2006 campaign. Additional data using halfraums and planar foils were also gathered. This choice of target should enable challenging our simulation capabilities on a wide range of physical situations, some giving rise to B-field generation and some

not, some in which radiation reabsorption is important and others in which it is not, and some amenable to lagrangian hydrodynamic modelling, while others require Arbitrary Lagrange Euler (ALE) methods. From 2016 onwards, this type of experiment is bound to be continued on LMJ, with interesting additional measurements of B-field generation in open or hohlraum geometry made possible by proton-radiography with the PETAL short pulse beam [petal]. The LIL LPI campaign is another example of an experiment specifically designed to improve our hohlraum modeling capability by addressing a particular physical phenomenon, and is described in more details elsewhere [6].

3. Capsule core shape

FCI2 with its standard settings has also been benchmarked against a series of capsule implosion experiments, most of them on Omega (in empty or gas-filled, rugby or cylinder hohlraums), as well as some NIC experiments (and most notably the rugby hohlraum shots of March and May 2013 [7]. Core shape is measured at maximum X-ray emission by decomposing the 2D capsule emission contour at 17% of its maximum on Legendre polynomials. Mode-2 asymmetry (so-called P2/P0) is our main observable here. In this respect, experiments and calculations are found to be in good agreement in empty hohlraums on Omega, while agreement is more variable on gas-filled experiments. Closer analysis reveals that the offset between measured and computed mode-2 asymmetry seems to be correlated to the fraction of inner-cone energy that gets absorbed in the outer-cone gold bubble or around the LEH, with higher amounts of such ill-deposited energy giving rise to poorer agreement on symmetry. The analysis of this correlation is still ongoing.

On NIF experiments, it comes as little surprise that capsule symmetry is a very strong function of cross-beam energy transfer [8]. For the same reason, symmetry is also a strong function of backscattered energy, in particular from the inner cones. In the analysis of rugby shot N130318, for which 40 kJ of SRS were measured on the inner cones [7], we observed that asymmetry could be changed (numerically) from $P2/P0 = -30\%$ to $P2/P0 = -54\%$ by subtracting an extra 20 kJ from the inner cone energy (figure 2). To justify this variation on backscattered energy, one should keep in mind that the usual way of handling backscatter in integrated simulations, i.e. by subtracting the backscattered power from the incident one, is an approximation, as backscattered photons actually propagate and are absorbed in part of the hohlraum plasma. An order of magnitude for this effect is assessed by computing, in a simulation for shot N130318, the collisional absorption of photons at the peak SRS wavelength propagating backward out of the hohlraum from their point of backscattering. Around the peak of the laser pulse, we find that $\sim 20\%$ of the backscattered energy is actually reabsorbed in the plasma, prompting us to revise the methodology for dealing with backscattered energy in our radiation hydrodynamics simulations.

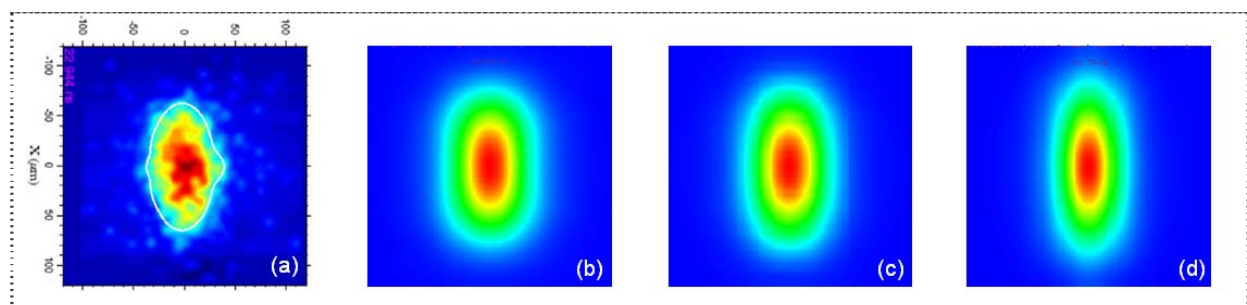


Figure 2. Experimental hot-spot shape measured on NIF for rugby shot N130318, $P2/P0 = -41\%$ [7] (a), FCI2 simulated shape using the net laser power (incident minus backscattered), $P2/P0 = -30\%$ (b), and with additional energy subtracted from the inner beams: -13 kJ, $P2/P0 = -39\%$ (c), -20 kJ, $P2/P0 = -54\%$ (d).

4. Capsule bang time

On a dozen of experiments, on Omega and on NIF, in cylindrical as well as rugby-shaped hohlraums, the time of peak neutron emission has been measured and compared to FCI2 simulations. The simulated bang time is consistently early compared to the measurement, on average by 200 ps on Omega and by 500 ps on NIF. On Omega, making up for this offset would require a systematic overestimate of the x-ray drive by 4%, or a systematic underestimate of the ablator thickness by 4 μm – two hypotheses that are deemed improbable. On NIF, this mismatch is very similar to that identified by LLNL and which led to the use of “multipliers” to relate the flux seen by the capsule to that computed in the hohlraum calculation [3]. This shortcoming casts doubts on our understanding and modelling of both the hohlraum and the capsule, and should therefore be solved with high priority. To address this problem, specific experiments have been conducted on the Omega laser, in which 1D (streaked) and 2D radiographs of a converging plastic capsule are measured and compared to simulations. The analysis of these data is ongoing, and initial results are presented elsewhere [9].

5. Hydrodynamic instabilities

The unexpected mix levels measured on NIF [4] highlight the need for improved understanding of hydrodynamic instability growth. Strong sensitivity to details of the radiation drive have been observed in numerical simulations of hydrodynamic instabilities of a typical NIF capsule, resulting in perturbations that do or do not invert during compression for radiation temperature changes on the order of 10 eVs in the picket or in the trough or the radiation drive pulse. We will carry out converging hydrodynamic instability experiments on Omega in 2014, leveraging on our implosion dynamics platform [9], to extend our database to higher convergence ratio than could be achieved on Nova. Obviously, the NIF “hydro growth” experiments [4] will also provide a wealth of information on this subject. However, simpler, planar geometry experiments can also be relevant here. An experimental concept derived from the Ablative Rayleigh-Taylor Science Use of NIF proposal [10] has been worked out to produce a surrogate flow to that of a NIF capsule, and we believe such experiments would be helpful in understanding the early phase of hydrodynamic instabilities in a fusion capsule. Such planar geometry will also be more amenable to early experiments on LMJ in the near future.

6. Conclusions

The CEA/DAM experimental ICF program is currently executed on Omega and LIL. Through the post-shot modelling of these experiments, and of NIF results, we aim at identifying the set of code parameters and physics options that leads to best agreement with the experiments over a large database of results. Integrated ICF experiments provide a wealth of data but their analysis can be complicated by the entanglement of various physical processes. In complement to these experiments, we therefore strive to design simpler experiments that focus on a specific physics issue. Examples of such efforts that are being carried out on Omega and will soon be transferred from LIL to LMJ have been given in this article.

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