# Computational Investigation of Impulse-Fluence Scaling in X-ray Illuminated Materials on the National Ignition Facility

Griffin Cearley [1,2] Peter Porazik [2] Laura Berzak Hopkins [2] Steve Moon [2] Carolyn Kuranz [1] Eric Johnsen [1]

[1]University of Michigan, Ann Arbor, MI. [2]Lawrence Livermore National Laboratory, Livermore, CA.

## Abstract

In a variety of high-energy-density (HED) systems, x-rays of a given energy are absorbed within a material up to a depth dictated by the material's opacity. This drives the heated surface layer to blow off, imparting impulse and sending a compressive wave into the bulk of the material. The impulse generated by x-ray energy deposition scales with the overall fluence of the incident x-rays. This scaling is sensitive to the x-ray source spectrum and the material opacity. Modeling the relationship between impulse and x-ray source is challenging; analytical models tend to be overly simplistic, entirely ignoring the sensitivity of this relationship to spectral detail. We employ a validated computational method to quantify the sensitivity of impulse to the source spectrum and overall fluence.

## Impulse-fluence scaling in HED systems

Many applications involve conversion of x-rays to material impulse through absorption processes

- Ablator impulse in indirect-drive inertial confinement fusion determines shock strength/timing and controls yield [1]
- Radiation hardness of crucial hardware components depends on x-ray conversion to impulse
- Objects threatening to impact Earth can be deflected with exo-atmospheric nuclear detonation [2]

Prior work relied on simplistic analytical modeling and experiments over limited parameter space

- Models (eg. MBBAY) do not account for complex physics [3]
  - material strength and non-ideal EOS
  - melt/vaporization/ionization physics
  - spectral dependence of absorption and x-ray source
- Z-machine experiments operated in narrow range of fluences [4]

## 2019 NIF experiments

Array of material samples irradiated by x-ray emission sources

- Photon Displacement Interferometry (PDI) measures displacement at rear of samples
- DANTE [5] provides time-integrated spectra from different emission sources

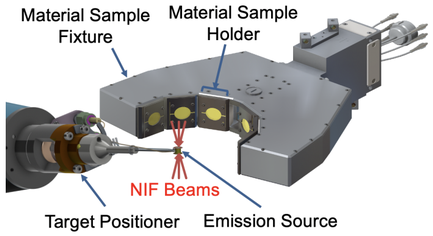


Figure 1: Illustrative diagram for NIF experiments.

NIF results allow us to validate our simulations

- Results are sensitive to phase change and EOS/stress models in this regime

We use validated simulations to study relationship between source spectrum/overall fluence and impulse generation

## Numerical method: Mercury and Ares

We use the Mercury Monte Carlo code [6] to simulate x-ray energy deposited from source into material samples

- We compute absorption of 3 million marker particles distributed in energy according to DANTE spectra obtained from experiments

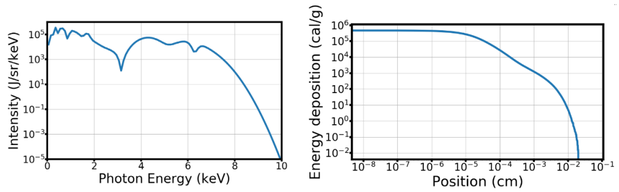


Figure 2: Left: Time-integrated DANTE emission spectrum, Xenon. Right: Energy deposition profile in Ti-6Al-4V sample.

We use the Ares radiation hydrodynamics code [7] to simulate 1-D hydrodynamics resulting from photon energy deposition

- Initial energy distribution profile imparts impulse to material via a compression wave

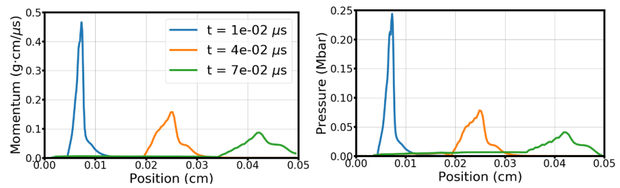


Figure 3: Momentum and pressure profiles in Ti-6Al-4V sample, 72 cal/cm$^2$ fluence.

## Numerical method: Validation

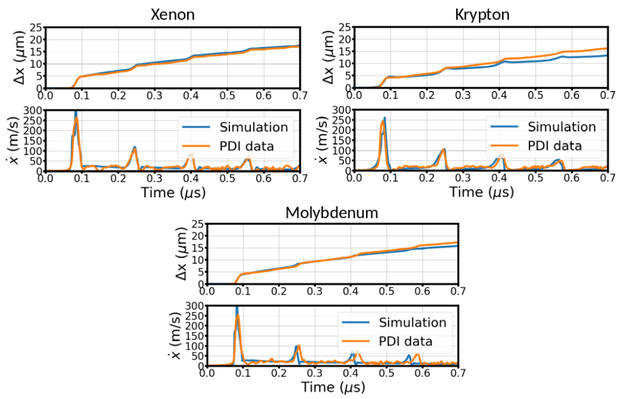


Figure 4: Lagrangian tracer displacement and velocity vs. experimental PDI data at rear of tamped Ti-6Al-4V sample, sources indicated in titles.

Simulated displacement of sample rear surface agrees well with PDI data

- Magnitude and shape of compression wave agrees with experiment to high level of fidelity

We have established confidence in values of initial impulse simulated using our numerical method and physical models

## Impulse-fluence scaling

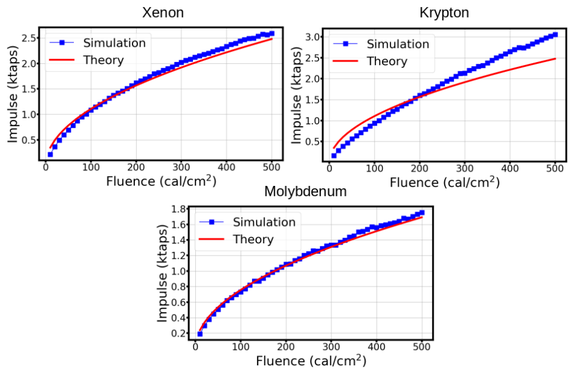


Figure 5: Impulse-fluence scaling in tamped Ti-6Al-4V sample, sources indicated in titles

Theoretical high-fluence scaling: $Impulse \propto Fluence^{1/2}$

For different source spectra, shape of fluence-impulse curves vary significantly

- Shape of curve depends on source spectrum
- Specific bands of the source spectrum have a greater impact on sample impulse
- Theoretical scaling [3] assumes a single material absorption value, does not account for source spectrum

Spectral sensitivity study quantifies how an increase in fluence of a specific band of the spectrum influences impulse

## Impulse-spectrum sensitivity study

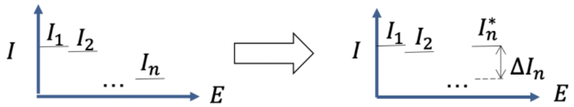


Figure 6: Left: Cartoon of DANTE intensity spectrum $I(E)$ discretized into intensity bins $I_1, I_2, ..., I_n$. Right: Perturbed spectrum where the $n$-th bin has been perturbed to $I_n^* = I_n + \Delta I_n$.

For a given material with a constant and uniform opacity, the impulse $J$ depends only on the source intensity:

$$J = J(I(E)) \approx J(I_1, I_2, ..., I_n)$$

We can write a change in impulse as:

$$dJ = \frac{\partial J}{\partial I_1} dI_1 + \frac{\partial J}{\partial I_2} dI_2 + ... + \frac{\partial J}{\partial I_n} dI_n$$

To estimate the sensitivity of $J$ with respect to the intensity of each $I_1, I_2, ..., I_n$, we perturb each bin independently and approximate these derivatives using forward finite differences:

$$\text{Impulse-spectrum sensitivity of bin } i = \frac{\partial J}{\partial I_i} \approx \frac{\Delta J}{\Delta I_i}$$

Quantification of the spectral sensitivity will help us understand impulse-fluence scaling

- Impulse-spectrum sensitivity will inform what bands of the spectrum most influence scaling

## Impulse-spectrum sensitivity study, cont.

Impulse-spectrum sensitivity appears to be dominated by features in absorption spectrum

- Jump in sensitivity around 5 keV corresponds to Titanium absorption edge

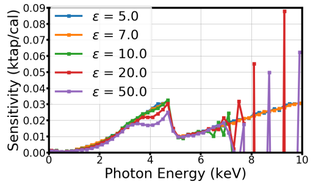


Figure 7: Convergence of impulse-spectrum sensitivity curve for Ti-6Al-4V and Xenon source, with $\Delta I_i = \epsilon I_i$

We achieve convergence as $\epsilon \to 0$

## Summary

- We are using Mercury and Ares to simulate photon deposition and impulse generation in material samples exposed to different x-ray emission sources
- We have validated our method and associated models using data from 2019 NIF experiments
- We examined impulse-fluence scaling for a Ti-6Al-4V sample exposed to three different sources
- We conducted impulse-spectral sensitivity studies to quantify the dependence of scaling on source spectrum

## Future Work

Future work will involve data-driven modeling and uncertainty quantification

- Due to complex governing physics, accurate analytical modeling is difficult if not impossible
- Data-driven modeling using impulse-fluence scaling and impulse-spectrum sensitivity can provide an accurate and simple model for calculating impulse from a given source
- Uncertainty in DANTE source data and material parameters will be propagated to constrain error of impulse calculation from data-driven model

## References

[1] H. F. Robey et al. Shock timing experiments on the national ignition facility: Initial results and comparison with simulation. *Physics of Plasmas*, 19(4):042706, 2012.

[2] R. J. Lawrence et al. Analytic models for pulsed x-ray impulse coupling. *AIP Conference Proceedings*, 1426(1):883–886, 2012.

[3] R. J. Lawerence. The equivalence of simple models for radiation-induced impulse. In *Shock Compression of Condensed Matter–1991*, pages 785 – 788. Elsevier, Amsterdam, 1992.

[4] J. L. Remo and M. D. Furnish. Analysis of z-pinch shock wave experiments on meteorite and planetary materials. *International Journal of Impact Engineering*, 35(12):1516 – 1521, 2008. Hypervelocity Impact Proceedings of the 2007 Symposium.

[5] E. L. Dewald et al. DANTE soft x-ray power diagnostic for national ignition facility. *Review of Scientific Instruments*, 75(10):3759–3761, 2004.

[6] R. J. Procassini et al. Verification and validation of Mercury: a modern, Monte Carlo particle transport code. Technical report, Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), 2004.

[7] B. S. Ryujin. Performance and portability in the Ares multi-physics code. Technical report, Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), 2015.

Views expressed here do not necessarily reflect the opinion of the United States Government, the United States Department of Energy, the Remote Sensing Laboratory, or the Lawrence Livermore National Laboratory. This work was performed under the auspices of the U.S. Department of Energy by Lawerence Livermore National Laboratory under contract DE-AC52 07NA27344. Lawrence Livermore National Security, LLC. This work is also funded by the U.S. Department of Energy NNSA Center of Excellence under cooperative agreement number DE-NA0003869

Lawrence Livermore National Laboratory
LLNL-POST-816418