Understanding Collision Mechanisms for Momentum Diagnostics in Ejecta Physics

A forward modelling study of the dynamic elasticity/inelasticity at the collision interface of PDV diagnosed Asay foils and windows

2026 PDV Workshop,
20260518

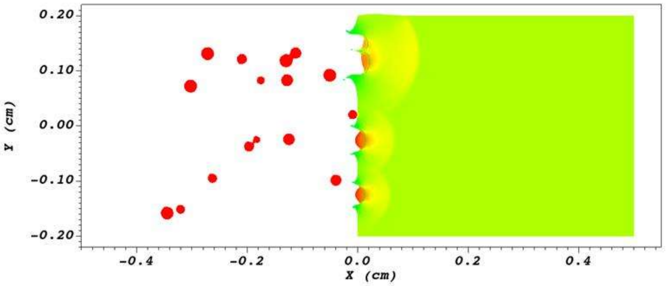
Daniel Champion
Fady Najjar
LLNL

Prepared by LLNL under Contract DE-AC52-07NA27344.

LLNL-CFPRES-2019174. Work performed under the auspices of the U.S. DOE by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC.

Motivation and background

- It is generally expected (optimistically) that the collisions between ejecta particles and Asay foils/windows are (perfectly) inelastic
    - No bouncing, no splashing, no spillage…
    - There are some experiments that have been performed to assess this statement, confirming and conflicting…
    - Why?: it makes the analysis possible and easy
- At the same time, displaced material from a collision (splashing) is expected
    - ‘Splashing’ behavior conflicts with inelastic assumptions and will result in some amount of overestimation of momentum in the foil/window.
- The properties of splashing, (and the downstream effects), has the potential for creating the conditions for ***complex dynamic momentum transfer behavior.***
    - Could depend highly on collider velocity, cloud density, and elapsed time!
- **This simulation study is an attempt at investigating and characterizing the potential for this complex dynamic behavior and to make predictions as to the impacts on experiment data (namely PDV).**



12.7mm diameter impactor, 90mm Al target, 6.8 km/sec impact velocity. (Image courtesy ESA).

Presentation roadmap

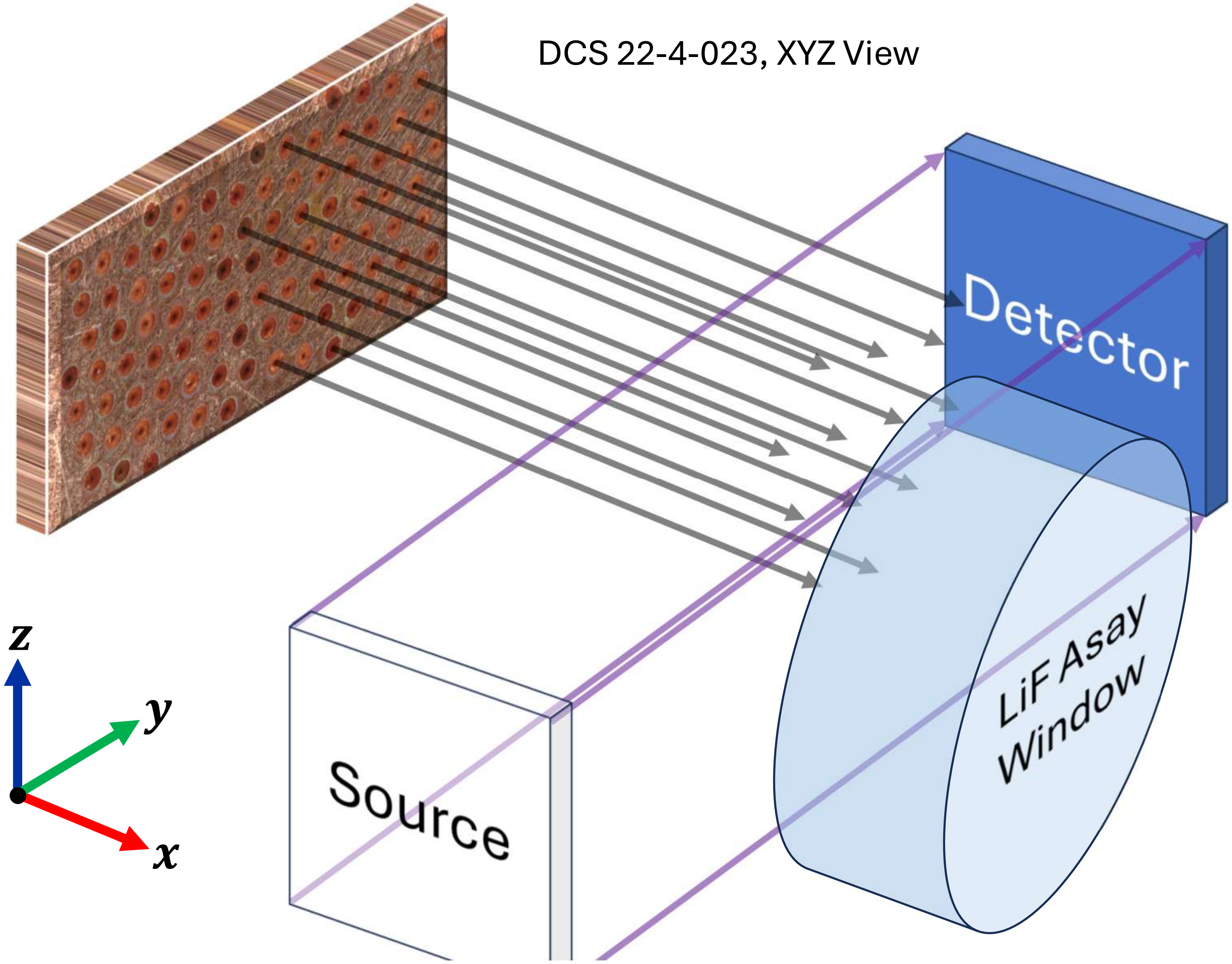
1. Experimental data and results from APS – DCS showing collision mechanisms.
2. Prior work, results, and theory related to this topic
   - Collision mechanics hypotheses
3. ARES forward modelling, simulation approach, and experiments
4. Simulation study results
5. Wrap-up and conclusions/summary

BLUF: Splash momentum approaches ≈ 10% of deposited momentum, and can amount to 5x → 1x the deposited mass with a time dependance. (2-4 km/sec micron scale particles)

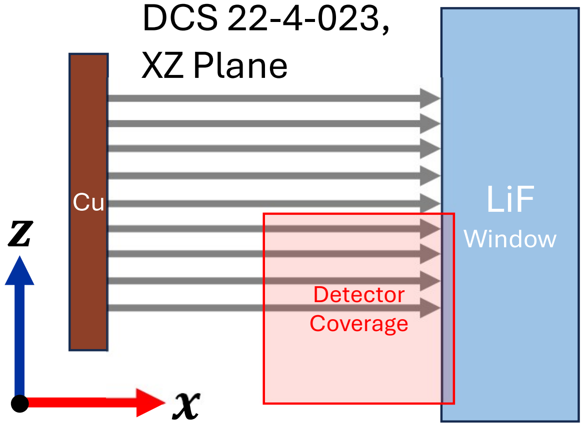
Experimental data and results of momentum diagnostic collision mechanisms

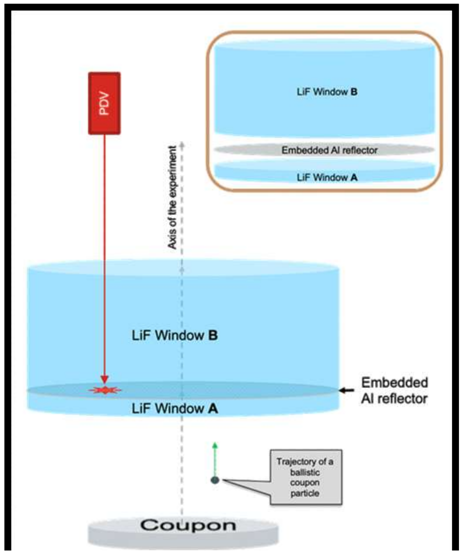
Cinematic radiography for an experiment at APS – DCS observing the dynamics at the collision surface of an Asay window: DCS 22-4-023

DCS 22-4-023, XYZ View

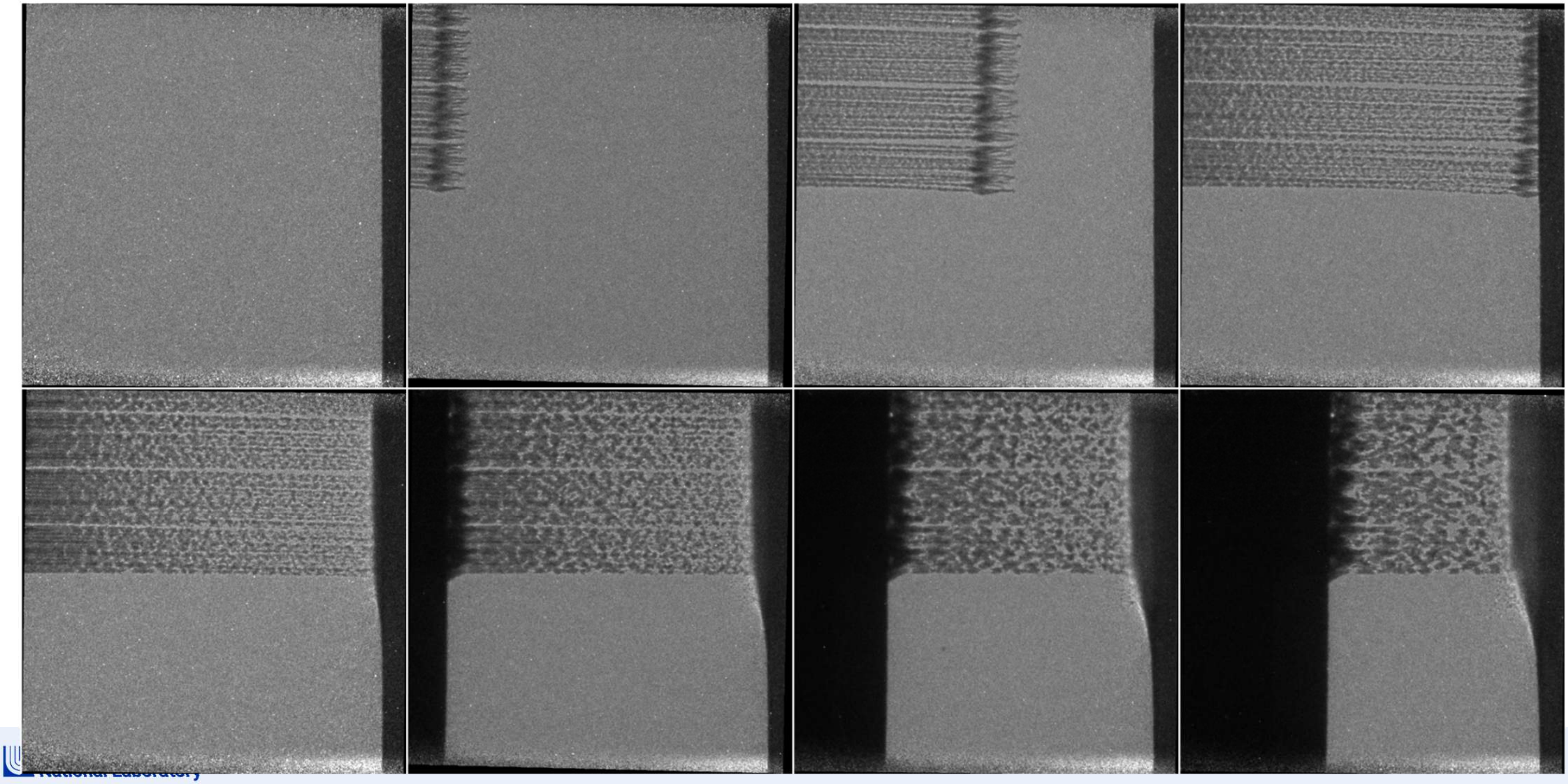


DCS 22-4-023, XZ Plane

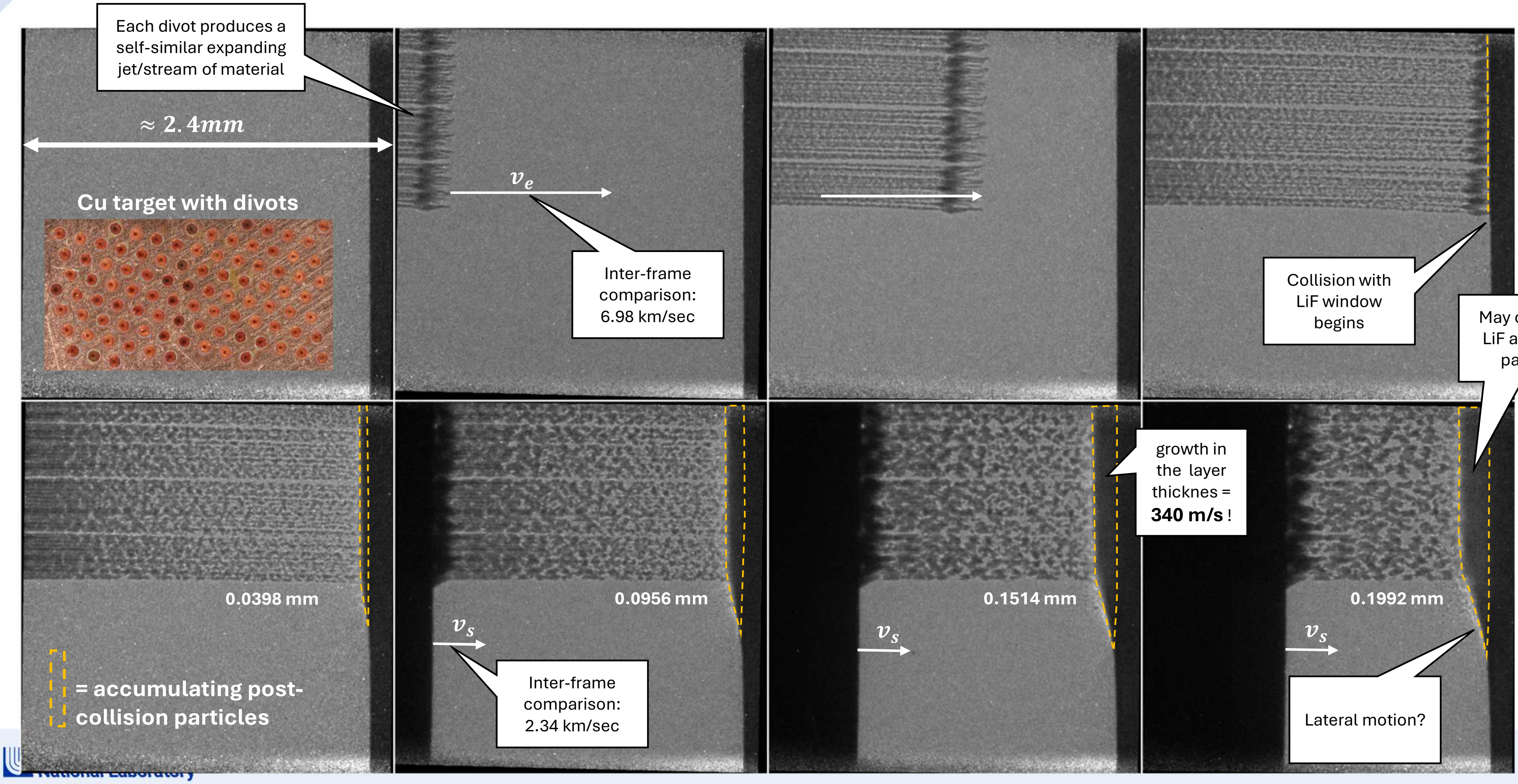




Cinematic radiography for an experiment at APS – DCS observing the dynamics at the collision surface of an Asay window: DCS 22-4-023



Splash or accretion layer growth on a LiF window? DCS 22-4-023



Each divot produces a self-similar expanding jet/stream of material

Inter-frame comparison: 6.98 km/sec

Collision with LiF window begins

May consist of LiF and/or Cu particles

growth in the layer thicknes = **340 m/s** !

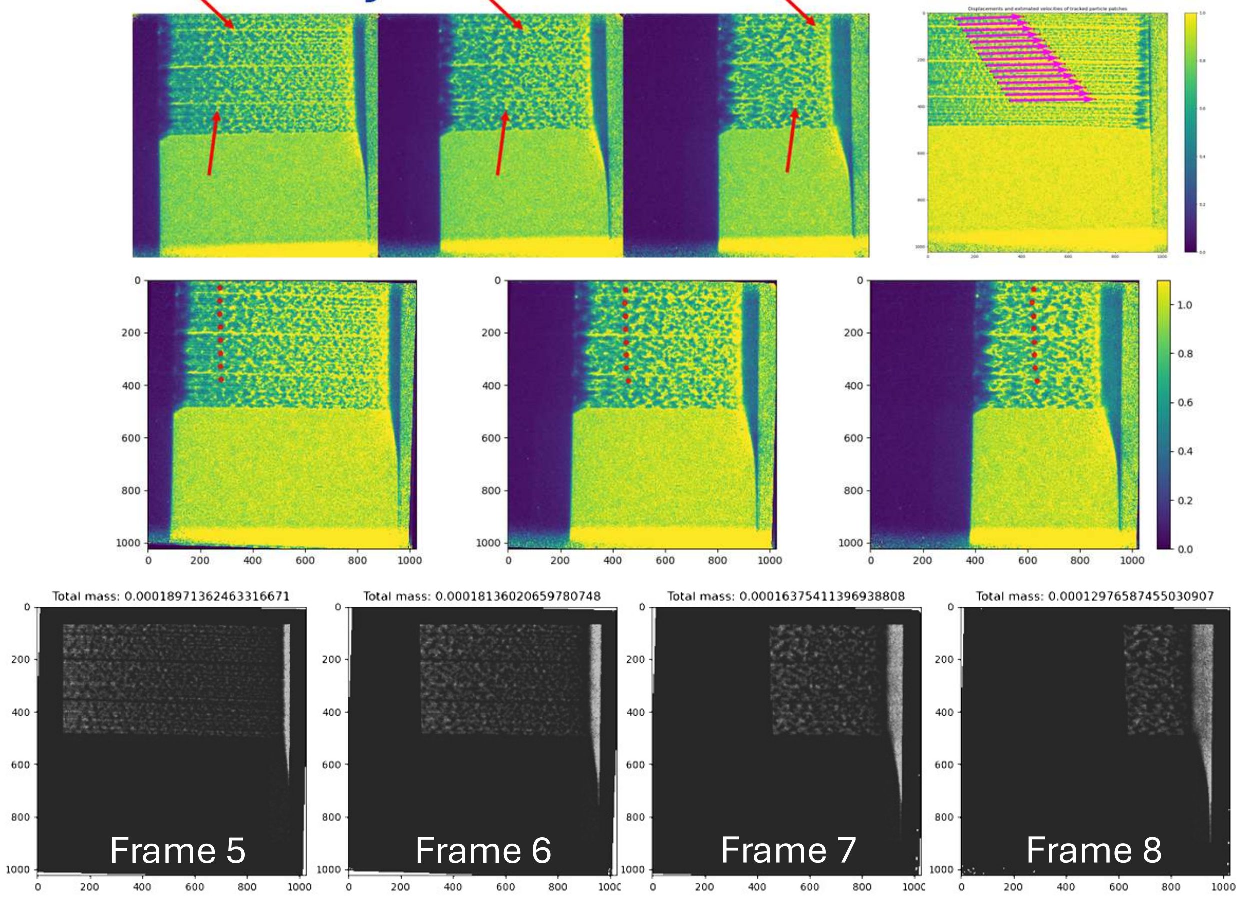
Inter-frame comparison: 2.34 km/sec

Lateral motion?

= accumulating post-collision particles

Material tracking in DCS 22-4-023 allows for isolation of a constant mass region for detailed analysis of the collision phenomenology

- Features in the jet streams ***self-similarly expand*** and repeat in subsequent frames (red arrows).
- Using an exhaustive self-similar-expansion cross-correlation technique [Sun, et al., 2024][1] we can track features to determine particle locations/velocities
- This enables us to track a closed region of particles from frame to frame and compare to radiographic mass estimates
- The growing collision/accumulation layer can also be segmented and processed to determine mass.



---

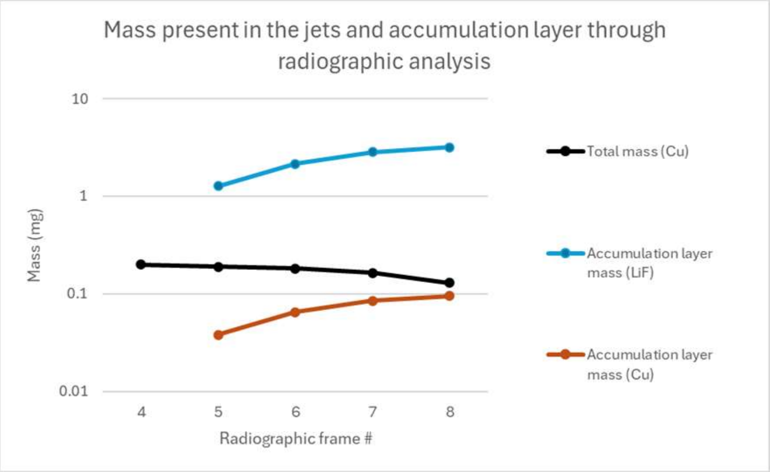
[1] Sun, Yuchen, et al. "Multi-frame x-ray radiography and image tracking for quantification of expansion in laser-driven tin ejecta microjets." *Review of Scientific Instruments* 95.12 (2024).

Mass recovery from Asay window and radiographic analysis is remarkably consistent, but also dependent on interpretation of the collision layer

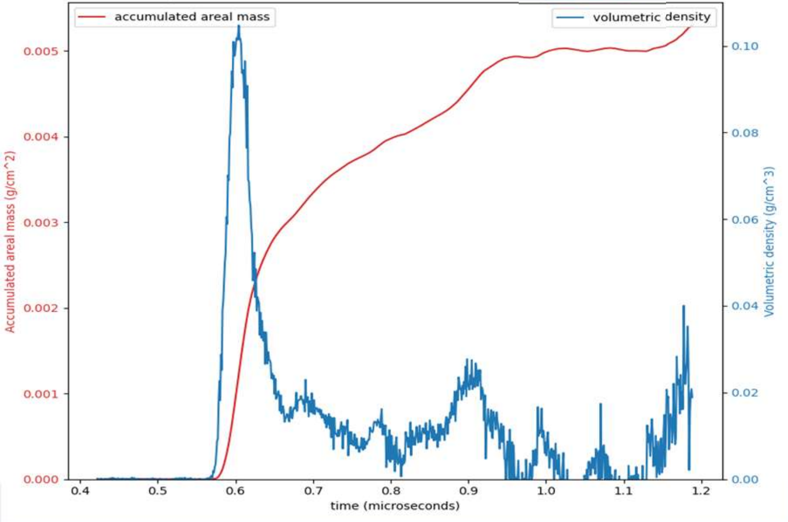
Is the visible accumulation layer predominantly Cu or LiF, or a combination of both?

- Difference in the mass attenuation coefficient for Cu and LiF result in substantially different mass estimates (figure at top-right)
    - Ending accumulation layer mass (8th frame): **Cu: 0.095 mg** **LiF: 3.18 mg**
- Compare to total mass of Cu jets (pre-collision): ≈**0.19 mg**

- Asay window analysis estimates an accumulation of $4\frac{mg}{cm^2}$ at the 8th radiographic frame, assuming perfect inelastic collisions (figure at bottom right).
- Radiographic analysis indicates the visible Cu pre-collision jets that collide through Frame 8 have an areal mass of $3.419\frac{mg}{cm^2}$, $\approx 20\%$ less.
- **Is the splash momentum (violation of inelastic collisions) resulting in overestimation of the Asay window mass estimates?**
- **Is the 3.18 mg LiF estimate more reasonable than the 0.095 mg Cu estimate?**
- **Do we need to take into account splash momentum when analyzing momentum diagnostics?**



Asay window areal mass (red) and volumetric density (blue)

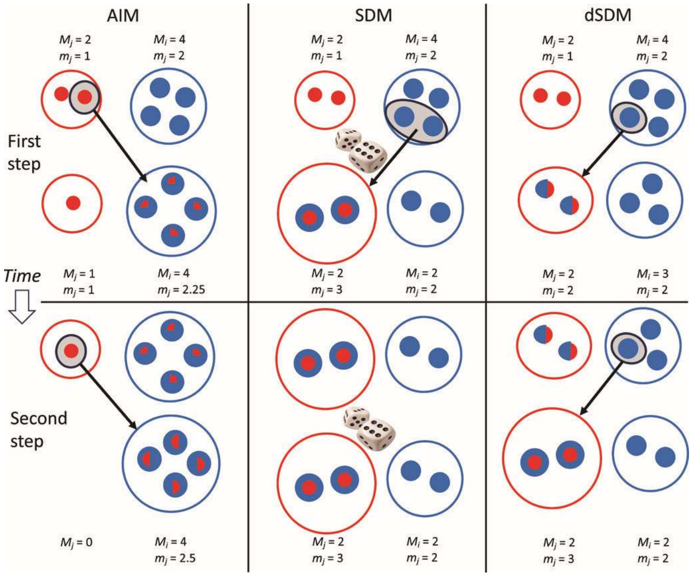


Prior work, theory, and related frameworks/models

Why there may be complex dynamics at play...

- The inbound colliders initially have prob=1 chance of colliding with the window/foil (and dumping a large proportion of momentum into it)
- As splashing or displaced material is produced, the odds change, a nonzero probability emerges for the likelihood of inbound particles colliding with splash material
- As splashing manifests and expands, it may dynamically change the likelihood of momentum transfer into the splash and the base material.
- In meteorology, a similar dynamic and stochastic effect is thought to be present in raindrop formation (stochastic coalescence), at each time point we roll a die and have particles collide, combine, bounce, break-apart, ...
    - one such macro-outcome is a raid drop, and another outcome is a self-sustaining cloud.

Stochastic coalescence[3] (droplet interactions in turbulent clouds)



[3]

---

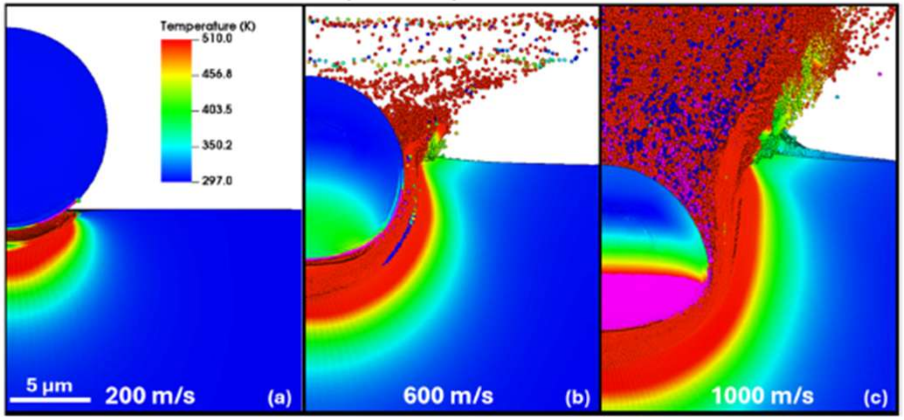
[3] Morrison, Hugh, et al. "Impacts of stochastic coalescence variability on warm rain initiation using Lagrangian microphysics in box and large-eddy simulations." *Journal of the Atmospheric Sciences* 81.6 (2024): 1067-1093.

Background: Coefficient of restitution

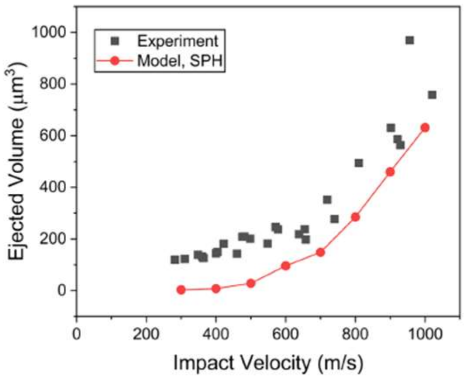
The coefficient of restitution (COR) is the classical quantitative parameter used to describe the elastic/inelastic properties of a 2-body collision (COR = e).

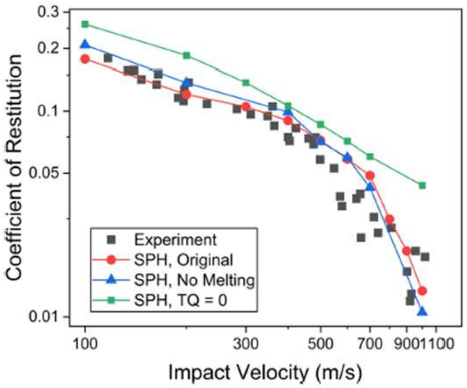
- Consider two bodies, A and B
  - pre-collision velocities: u_A, u_B
  - post-collision velocities v_A, v_B
- $e = \frac{|v_B - v_A|}{|u_A - u_B|} = sqrt\left(\frac{E_{k,post}}{E_{k,prior}}\right)$
  - Perfectly inelastic: $e = 0$
  - Perfectly elastic: $e = 1$
- For high velocity impacts the COR analysis becomes insufficient as ejected material is produced.
  - Differentiating the particle remnants from the ejected medium can be a challenge
  - Multiple particle interactions instead of 2-body physics.
- Research in single particle high-velocity impacts shows strong interactions between particle velocity and ejected material and COR[4].

Post-Impact Temperature Profiles



[4]

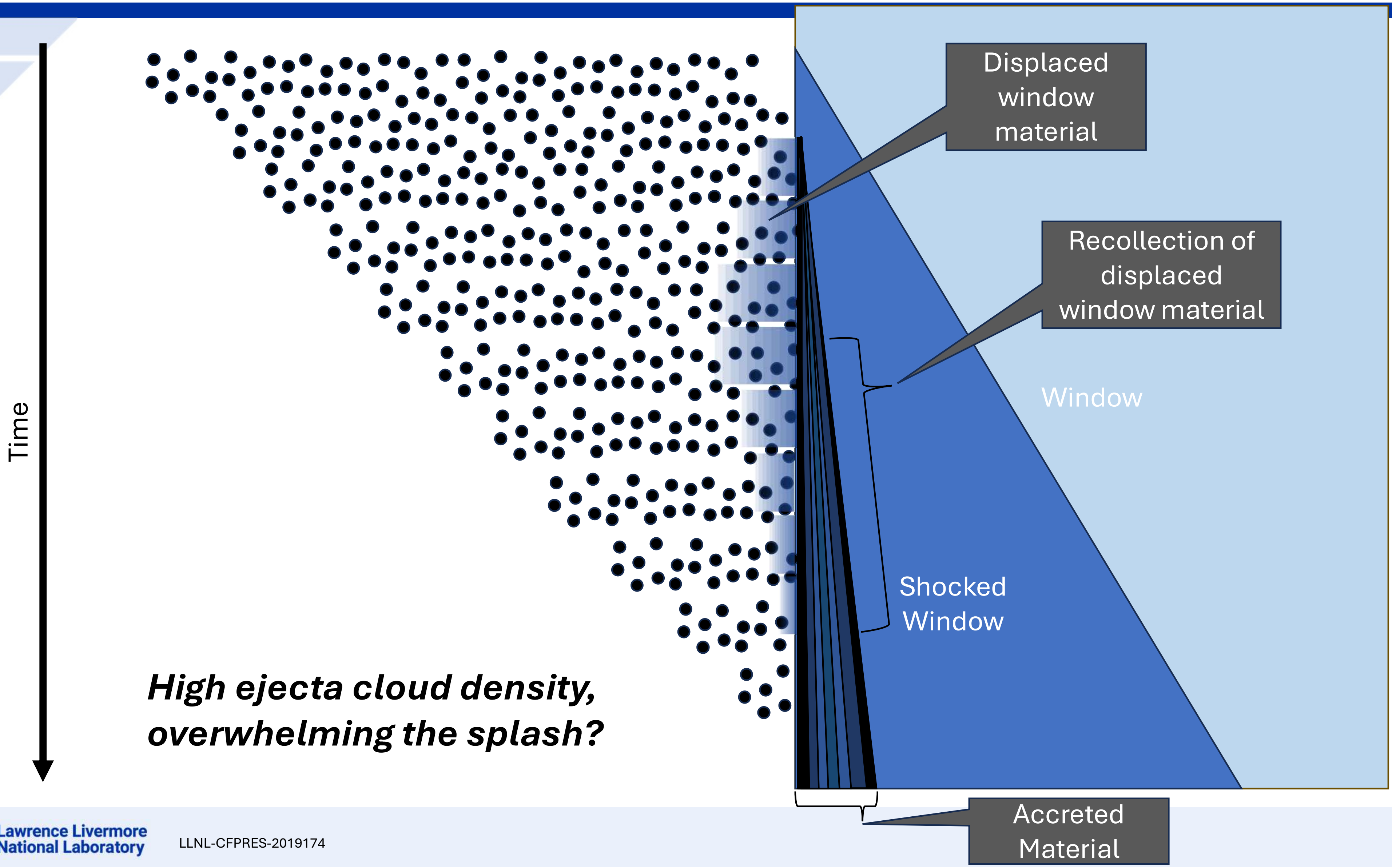




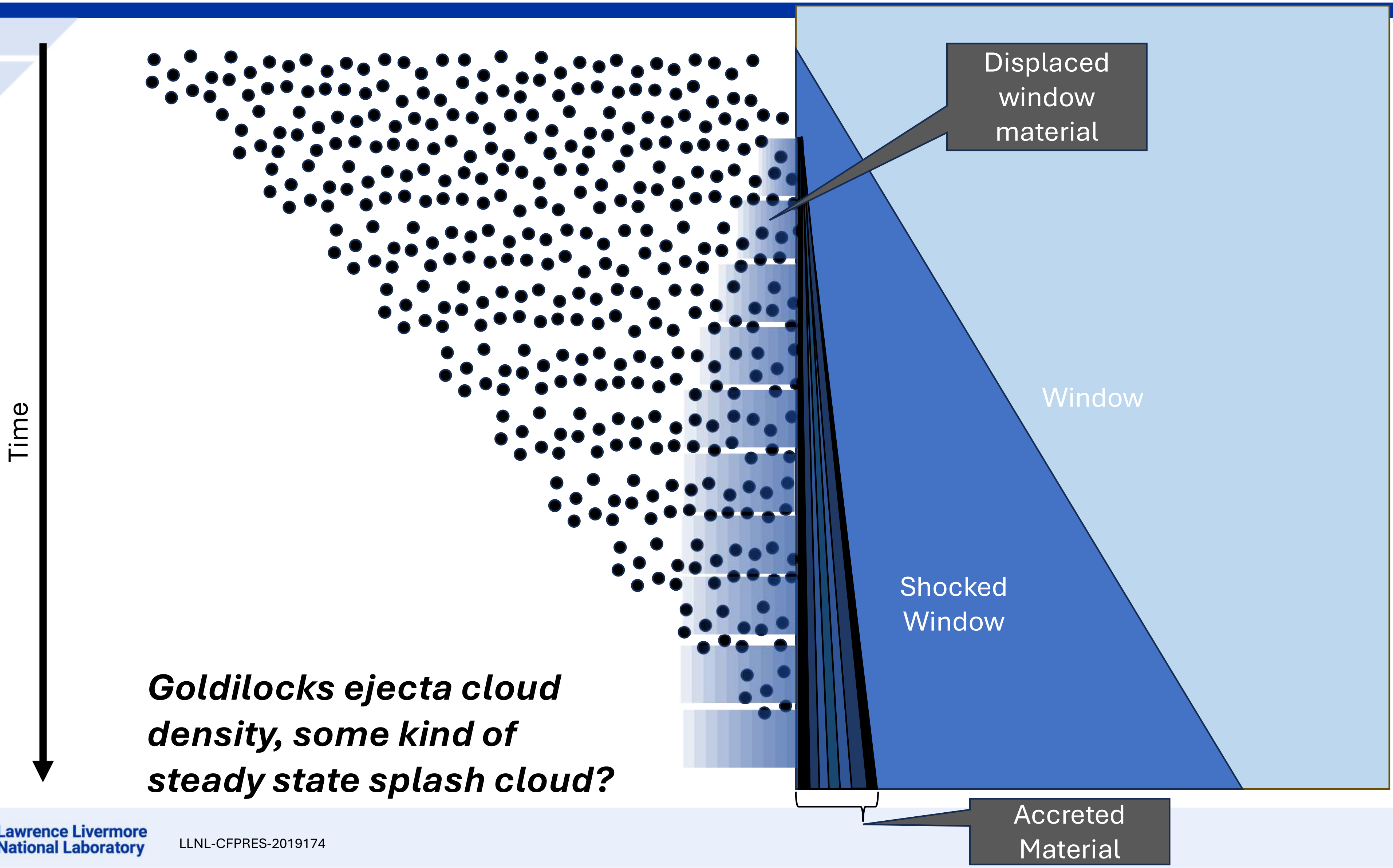
[4]

[4] Lucas, Tyler J., et al. "Modeling of melting and erosion in high velocity microparticle impacts." *Acta Materialia* (2025): 121488.

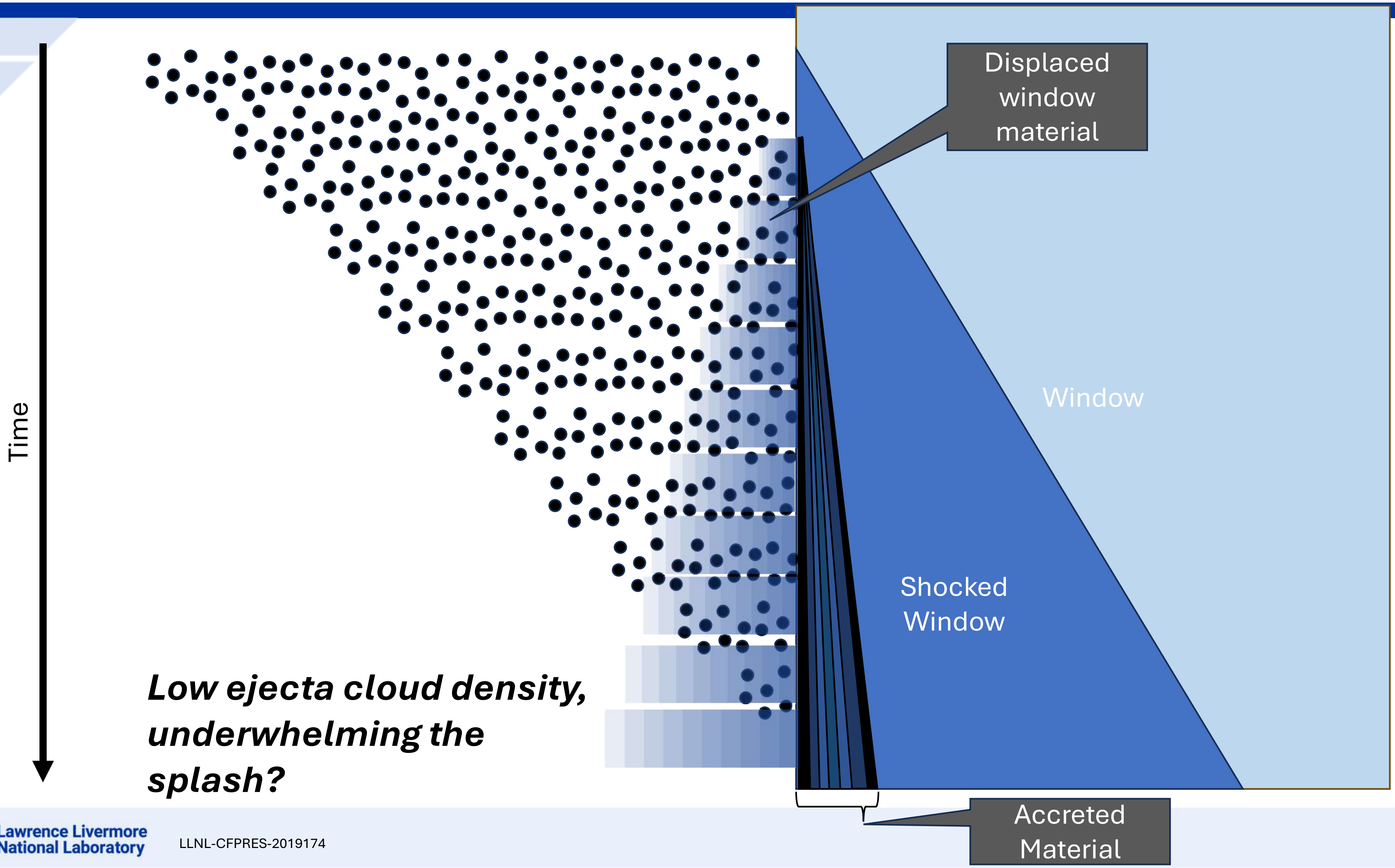
Three splash hypotheses applied to windows/foils



High ejecta cloud density, overwhelming the splash?



Goldilocks ejecta cloud density, some kind of steady state splash cloud?



Time

Displaced window material

Window

Shocked Window

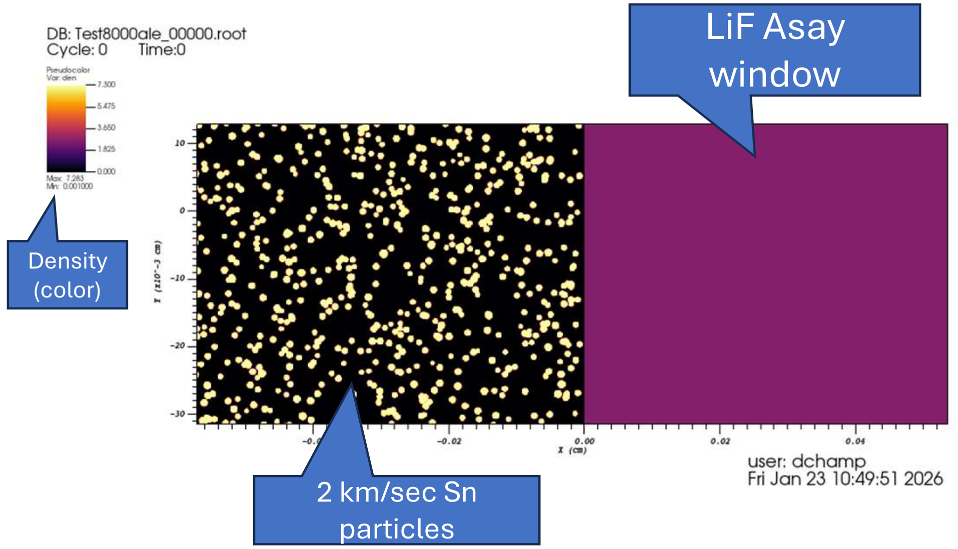
Accreted Material

Low ejecta cloud density, underwhelming the splash?

ARES simulation study details

Approach: Forward models of particle cloud collisions with diagnostics allow for detailed study of momentum dynamics

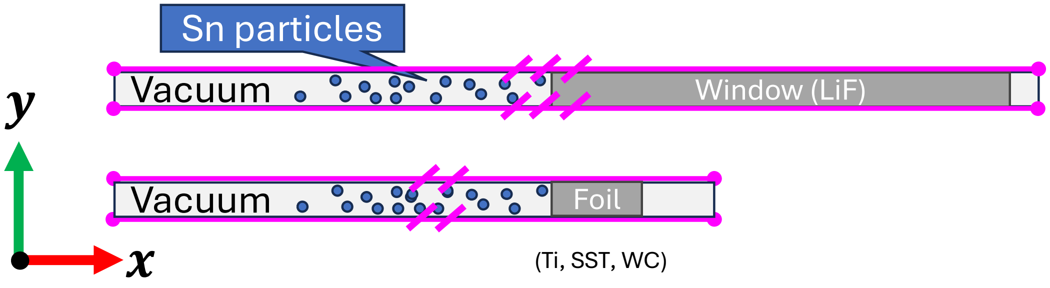
- We can prescribe known particle clouds in a controlled numerical experiment and calculate momentum statistics from the simulation data.
- The 2D and 3D simulations for this study were performed using ARES[2], a three-dimensional hydrodynamics simulation code developed at Lawrence Livermore National Lab (LLNL).
- High resolution simulations (0.1/0.2 micron meshes) were used to resolve 1.25 and 2.5 micron particles.
- A periodic boundary condition allows for a a narrow simulation domain without edge effects to manage computational complexity.



LiF Asay window

Density (color)

2 km/sec Sn particles

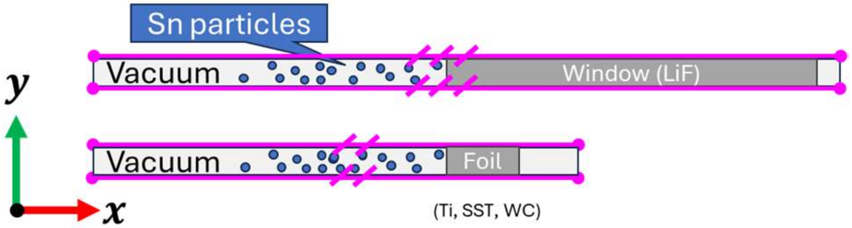


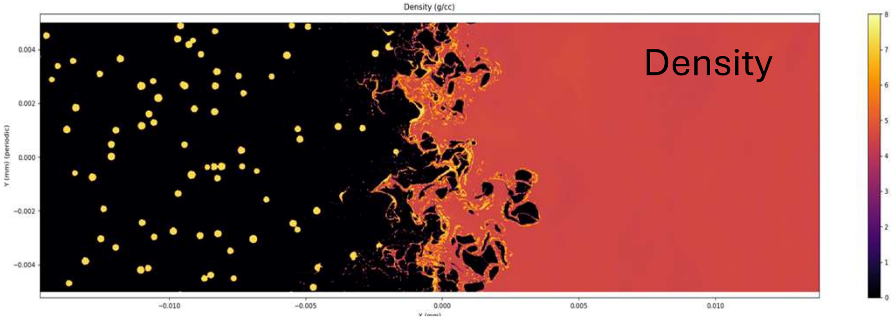
(Ti, SST, WC)

[2] Ryujin, B. S. (2015). *Performance and Portability in the Ares Multi-Physics Code*. Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States). OSTI ID: 1297654

Ranges of particle cloud properties and diagnostic conditions were tested to investigate momentum response and interactions.

- **Full Exponential Tests:**
  - A. Particle Velocity
    - 2, 3, 4 $\frac{km}{sec}$
  - B. Particle cloud density
    - 0.09, 0.18, 0.36 $\frac{g}{cc}$
- **Foil Material Tests**
  - Ti, SST (304), WC
    - (Steinberg-Guinan EOS with strength model)
  - Thickness:
    - 0.25mm thickness and varying thickness 112 $\frac{mg}{cm^2}$ constant areal mass foils
- **Stochastic Study**
  - 4x Foil Nominal, 4x Window Nominal
  - Randomly generated mass/density matching particle clouds



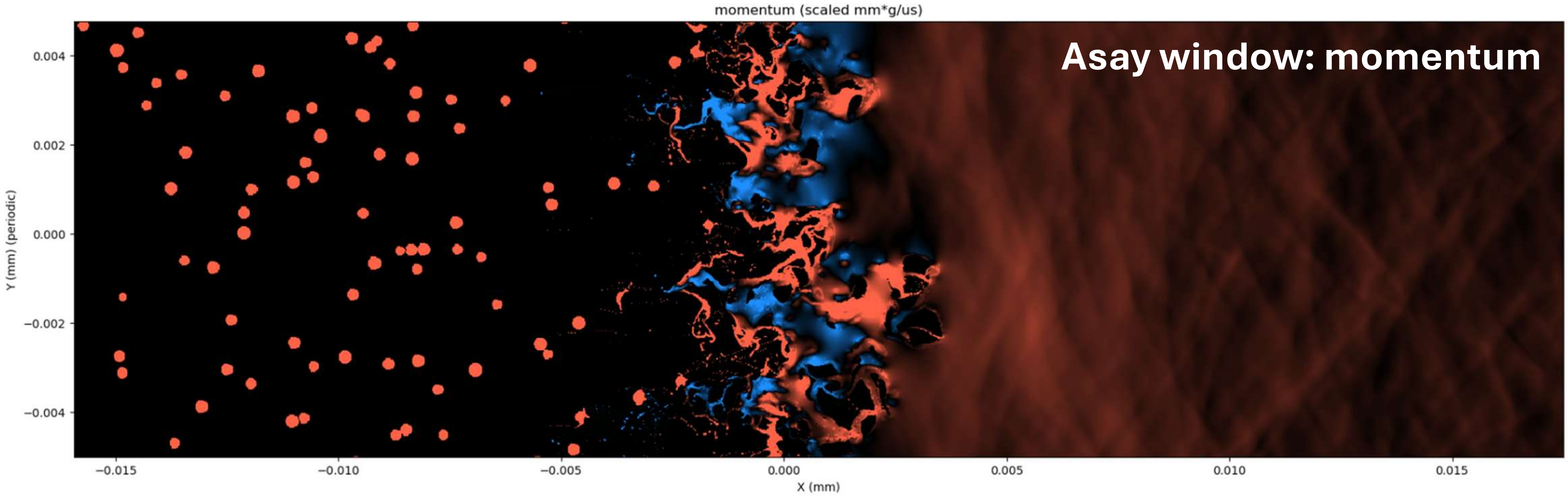


- Nominal Setup:
  - 2.5 micron diameter particles with 10% standard variation
  - 5mm thick Asay windows
  - 0.2 micron mesh, 100μm domain height (Y/Z)
  - 7.5mm (Window) or 3mm (Foil) long domain length (X)

[2] Ryujin, B. S. (2015). *Performance and Portability in the Ares Multi-Physics Code*. Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States). OSTI ID: 1297654

Analysis results – momentum in splash and target

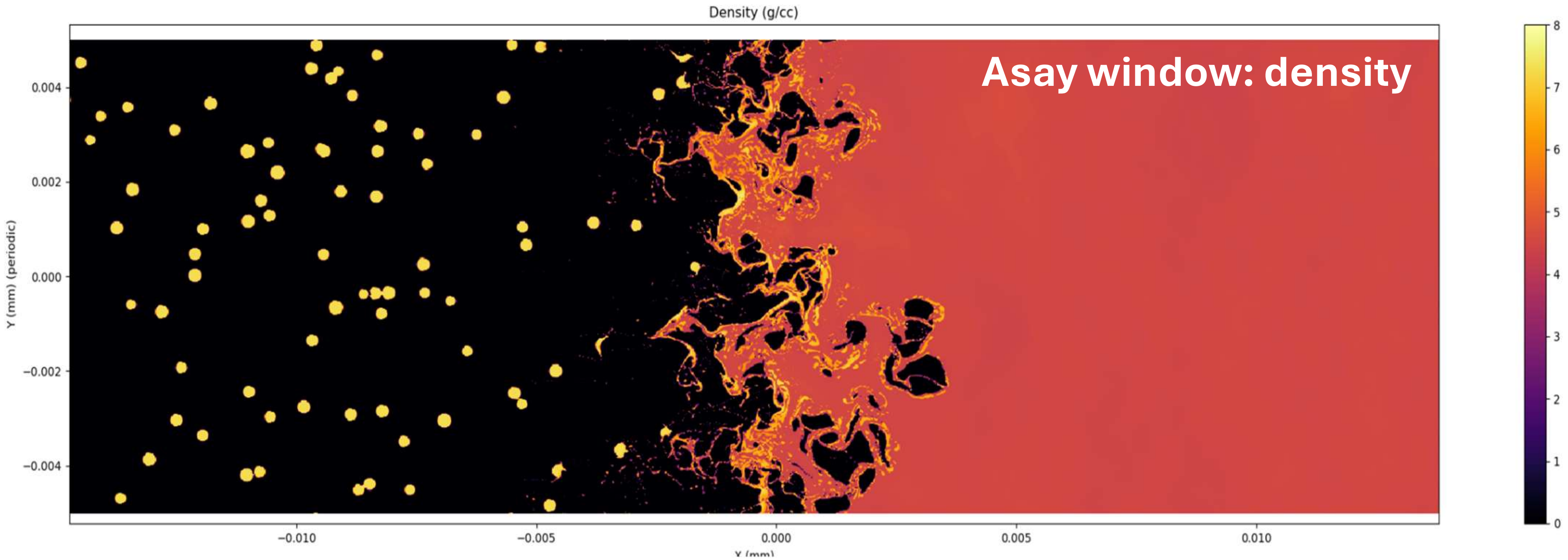
ARES momentum calculations and dynamics



Blue = splash momentum
Red particles = inbound collider momentum
Red medium (right) = momentum transferred to the window/foil

We capture the x&y velocity, density, pressure, and other parameters from the mesh to compute and isolate splash momentum/mass

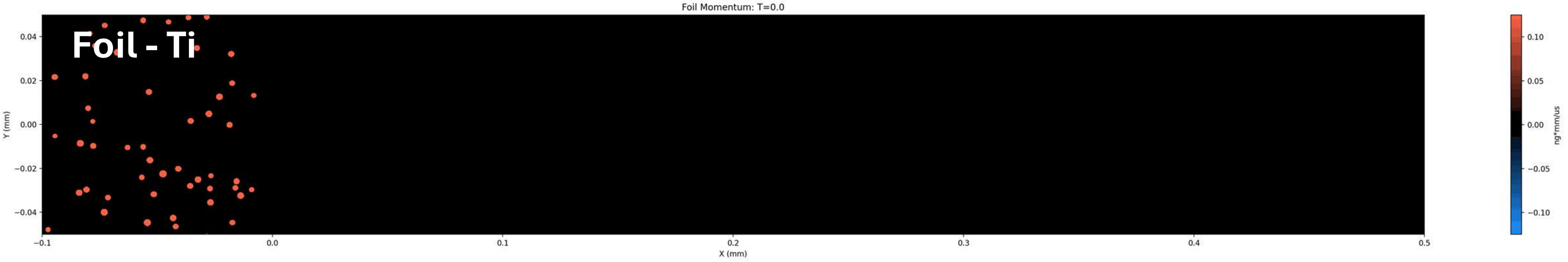
ARES momentum calculations and dynamics

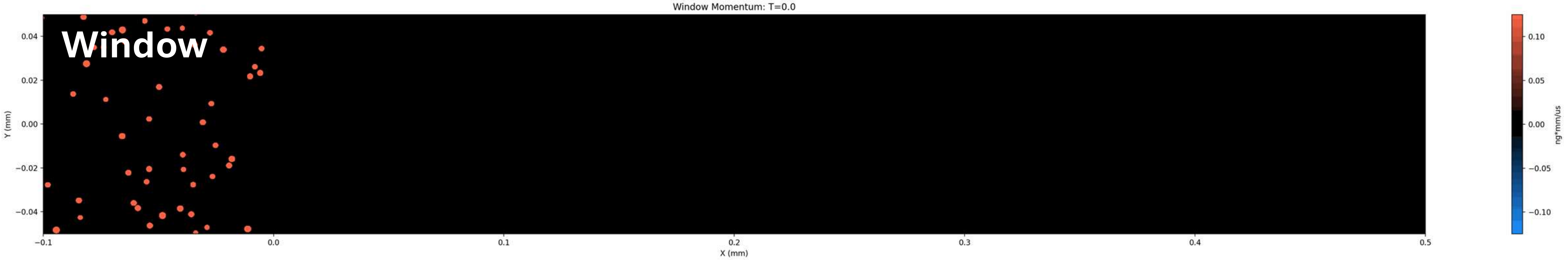


Blue = splash momentum
Red particles = inbound collider momentum
Red medium (right) = momentum transferred to the window/foil

Animated foil and window resolved models

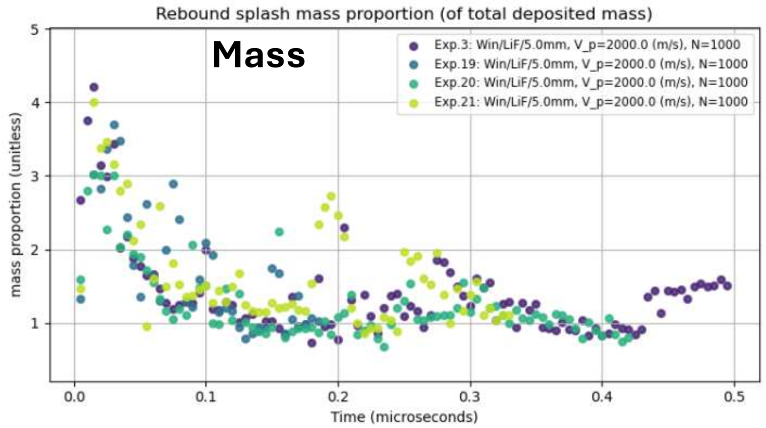
Red/Blue colormap is centered at 0 velocity (BTW: this isn’t necessarily the correct way to isolate splash…)

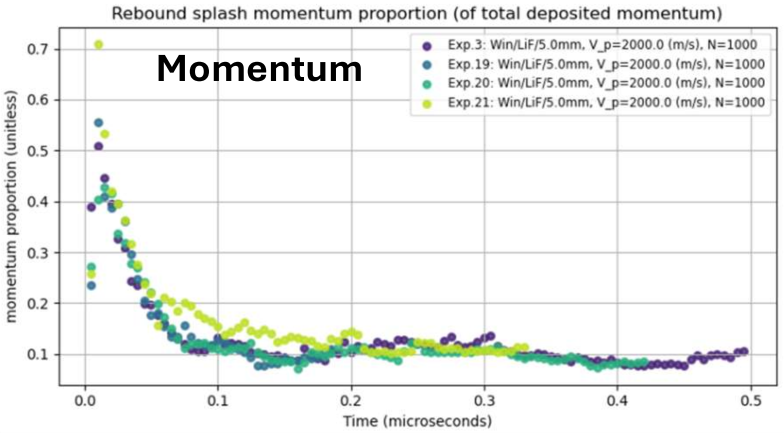




Variability and repeatability: Asay window

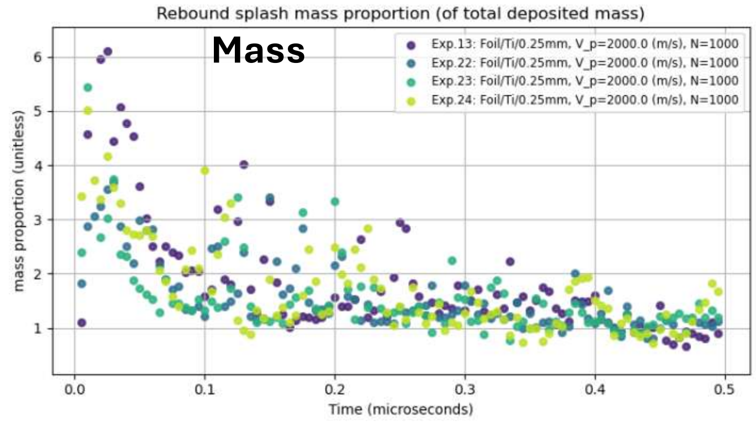
- Four simulations were with identical Asay window configurations (LiF, 5mm)
- The random particle initialization was the sole difference between runs (RNG determines initial particle positions).
- In the first 50ns the mass proportion of the ejected/rebound splash material initially reaches as high as 4x the deposited mass.
- The momentum proportion is substantially less, with initial momentum proportions reaching ~50%, and then decaying asymptotically to ~10% of total deposited momentum at 500ns.

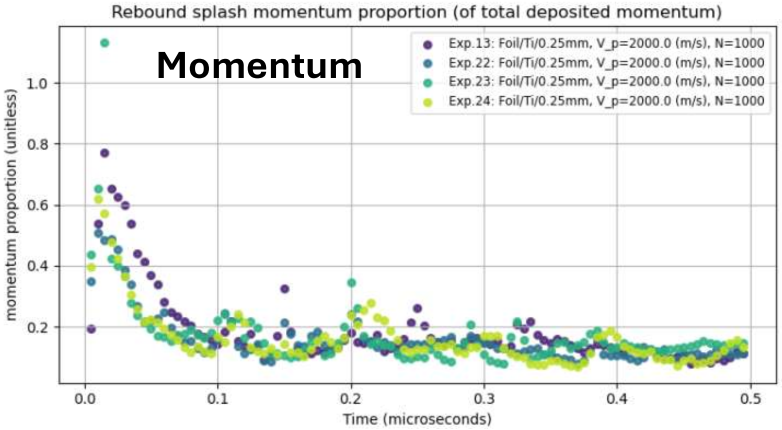




Variability and repeatability: Asay foil

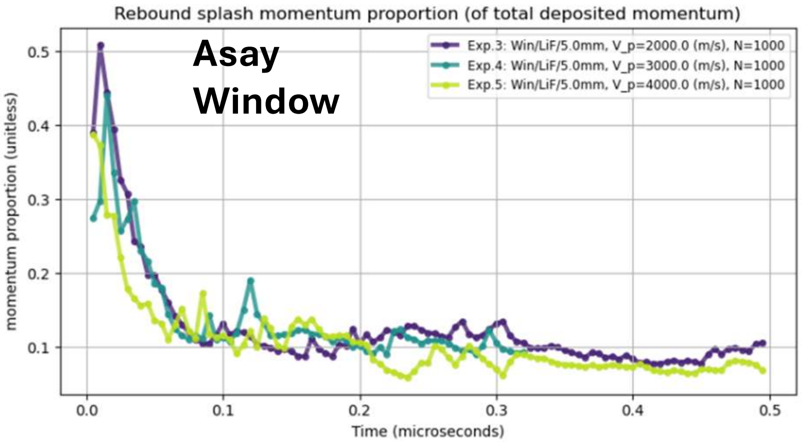
- Four simulations were with identical Asay foil configurations (Ti, 0.25mm)
- The random particle initialization was the sole difference between runs (RNG determines initial particle positions).
- Similar mass and momentum proportional behavior to Asay windows (initial and asymptotic)
- For Asay foils, we can start to see a periodic structure in the mass/momentum telemetry that corresponds to shock round-trips through the foil due to the sudden onset of collisions.
  - This periodic shock behavior is likely present in all Asay foil data, however sudden changes in cloud density are rare in most dynamic ejecta producing experiments.

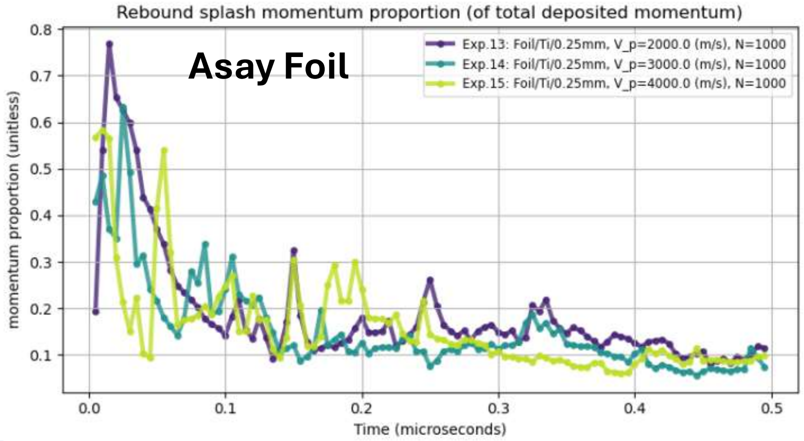




Particle velocity – momentum & mass

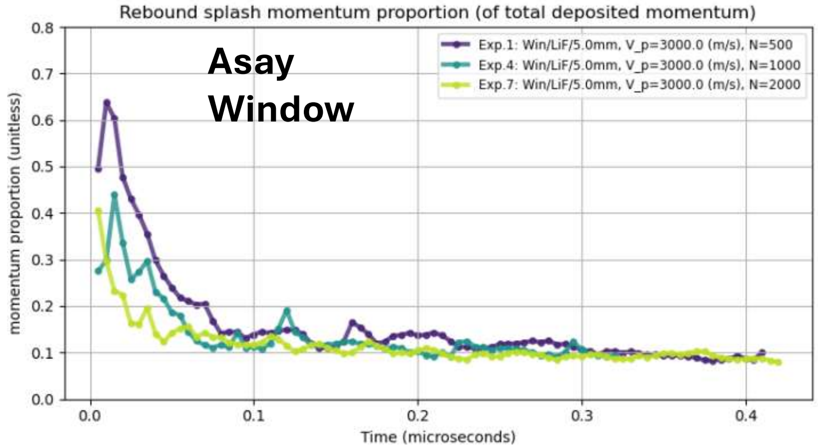
- Limited response to particle velocity, possibly a decrease in proportion of rebound splash momentum as inbound particle velocity increases?
- Asay windows more quickly converge to a 10% momentum proportion; foils may take longer to converge and show higher variability.
- Mass proportions show similar behavior across the tested particle velocity range.



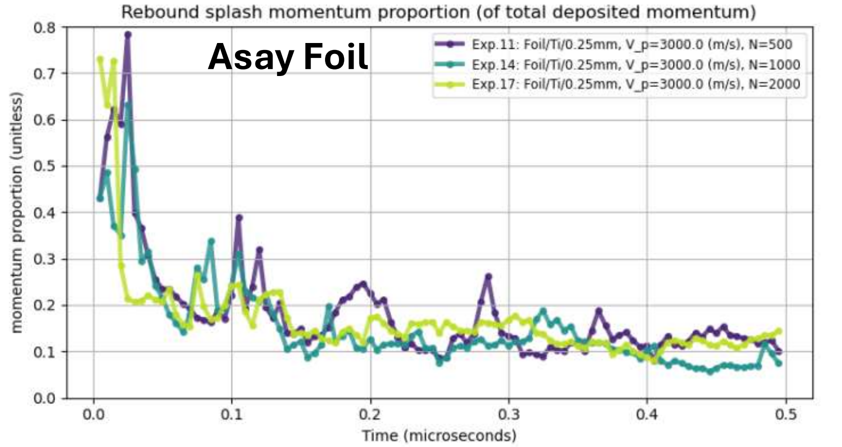


Particle cloud density – momentum & mass

- Higher particle cloud densities appear to result in higher rebound splash momentum proportions; the time duration to converge to the ~10% level may also increase.
- Periodic structure visible in the Asay foil data, with similar periodicity at all density levels.
- Mass proportions show similar behavior across the tested particle velocity range.



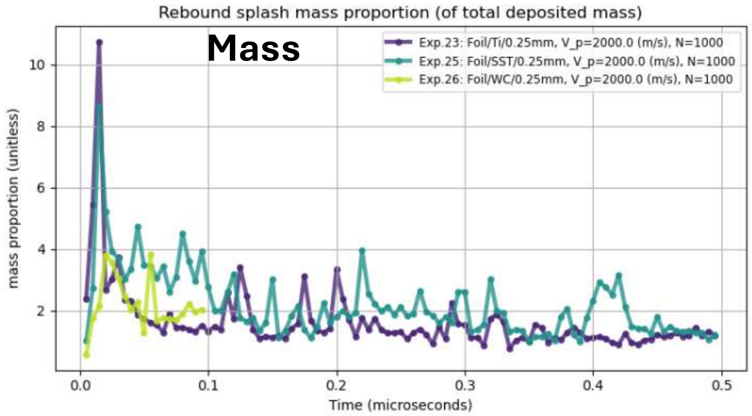
Rebound splash momentum proportion (of total deposited momentum)



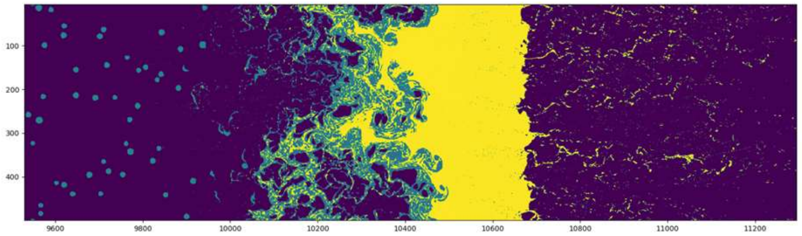
Rebound splash momentum proportion (of total deposited momentum)

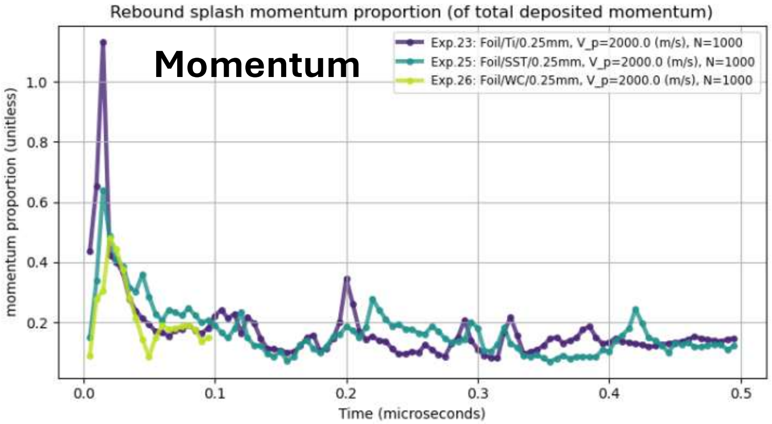
Asay foil material– momentum & mass

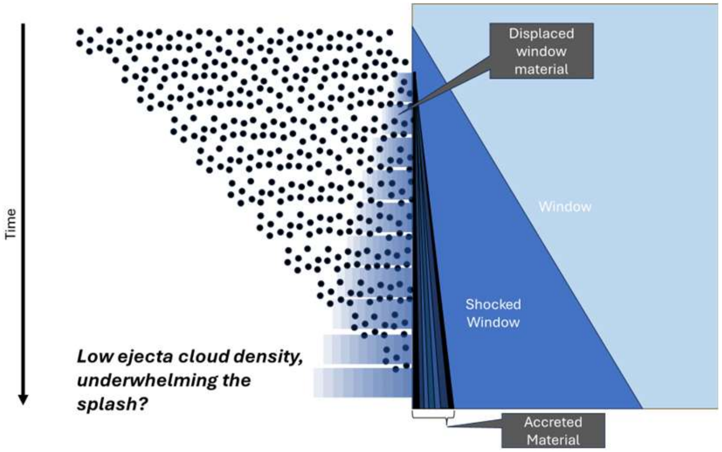
- Higher density (and strength) foils show lower rebound splash mass and momentum.
- The Tungsten Carbide (WC) simulations end early due to lost tracers. The back side of the WC foil showed significant ejected material after shock arrival.



Thin WC Asay foil at 500ns (density)





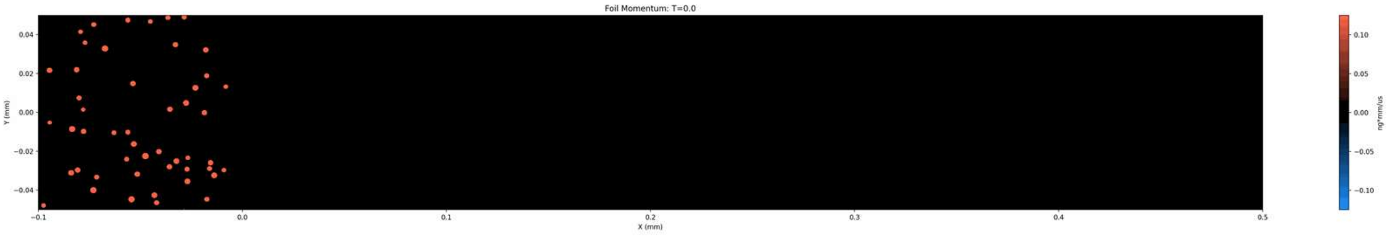


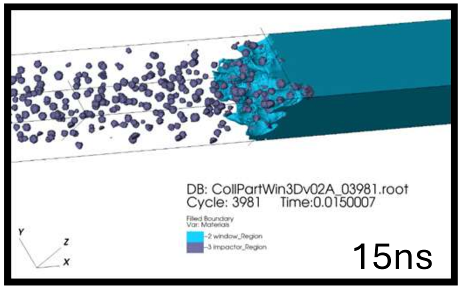
Low ejecta cloud density, underwhelming the splash?

Summary and conclusions

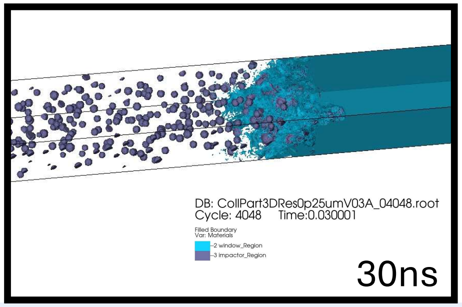
Summary, conclusions, and questions…

- ARES predicts time-varying proportions of splash momentum during extended ejecta diagnostic collisions
    - Subsiding after 100ns and converging at ~10% momentum, and 1:1 mass proportion (relative to mass deposited)
    - This indicates that PDV diagnostic measurements of the foil back could be elevated at the 10% scale in some circumstances.
- Going back to DCS 22-4-023, the 1:1 proportion of LiF to deposited Cu material is reasonable, albeit at higher velocities that tested here.
- Foils & windows:
    - Dramatic differences in how these diagnostics collect momentum.
    - Periodic structure is clearly present in simulations of Asay foils, this has the potential to disturb mass measurements and may need to be deconvolved from the dynamic data.
- Ejecta velocity cloud density:
    - Limited response detected due to particle velocity (2-4 km/sec range)
    - Decrease in momentum and mass proportion at higher particle cloud densities. This may indicate these rebound splash effects become less important as cloud density ramps up.
- Further/future work options:
    - 2D vs 3D collisions,
    - Particle-particle interactions
    - Non-uniform material arrival





15ns



30ns

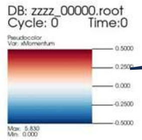
Thank you!
Questions?

Acknowledgements

- The authors thank Yuchen Sun, David Bober, Allison Saunders for a wide range of experimental and theoretical physics assistance and discussions on this topic.
- The authors thank the ARES support team for assistance with design, debugging, and optimizing the input decks used in this work.
- This work is based in part upon work performed at the Dynamic Compression Sector at the Advanced Photon Source supported by the Department of Energy, National Nuclear Security Administration, under Award No. DE-NA0003957. This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

Additional content

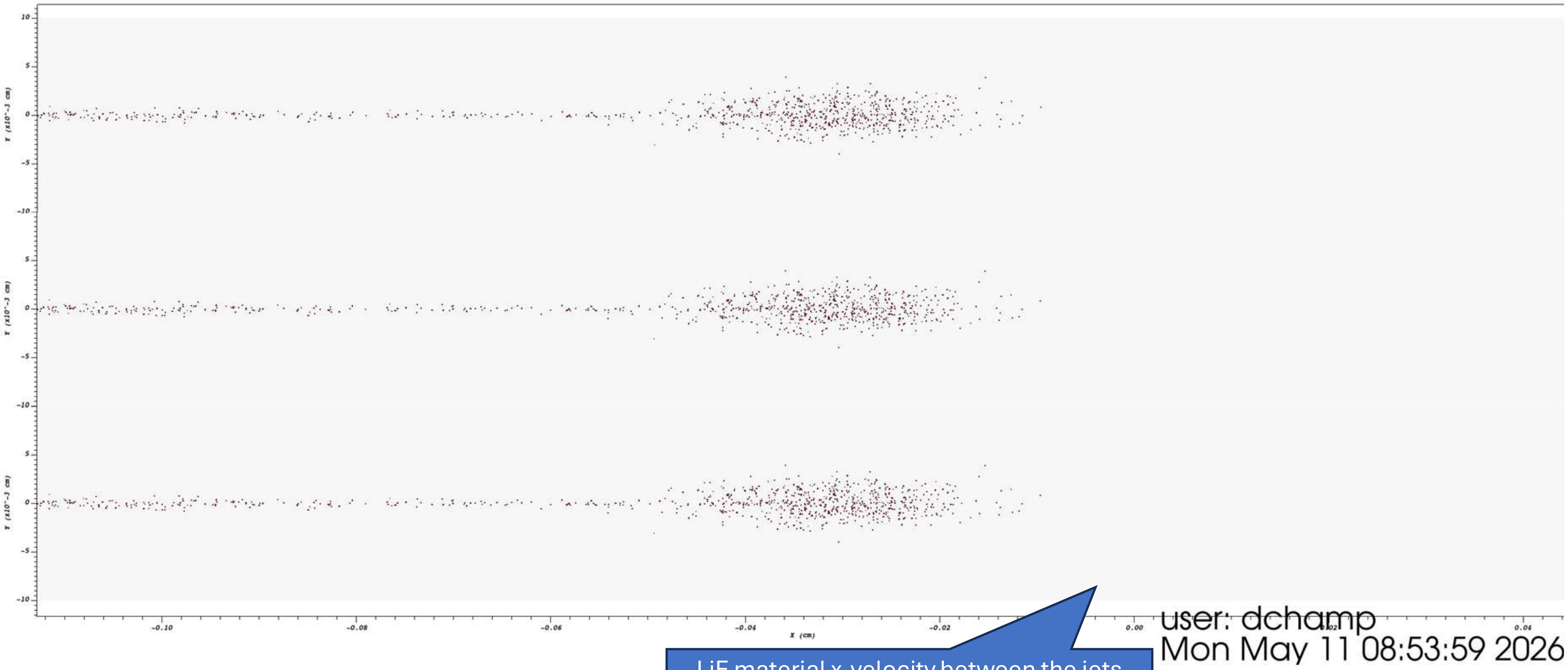
DCS 22-4-023 forward model



Animated plots show x-momentum $\left(\frac{cm \cdot g}{\mu s \cdot cm^3}\right)$

5ns per frame, 115ns duration

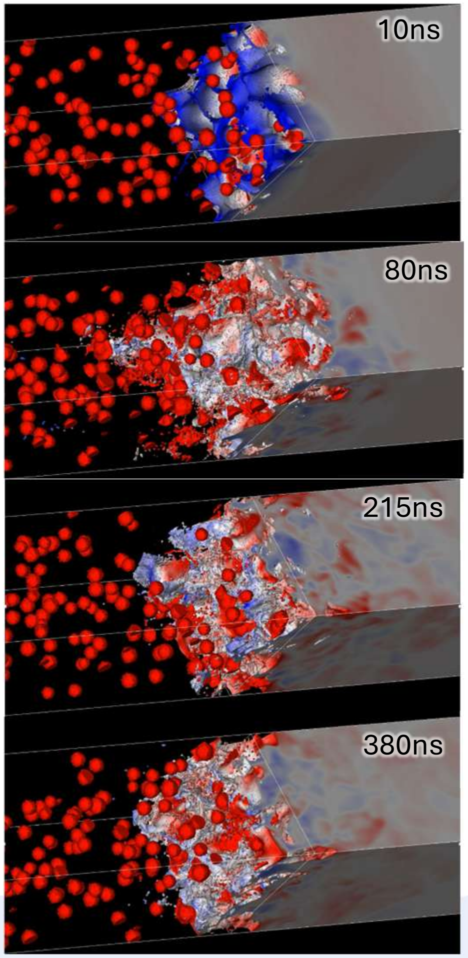
Jets have been shaped-in as a cloud of self-similarly expanding ~2.5 micron particles.



LiF material x-velocity between the jets varies between 0 and -1km/sec

3D Simulations of window collisions

X-velocity:
Red = +2km/sec
Blue = -2km/sec



Material:
Red = Sn
Cyan = LiF