Experimental Observations of Laser-Driven Tin Ejecta Microjet Interactions

MERIT
Metal Ejecta: Recollection, Interaction, and Transport

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HEDS Center Seminar
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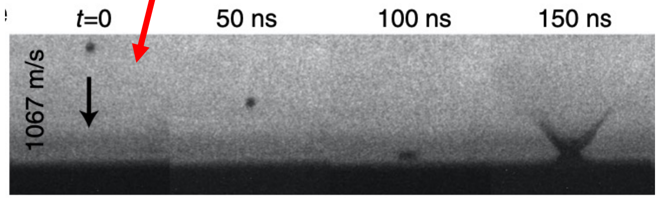
Ejecta microjets offer an experimental methodology to study the interactions of high-velocity particle streams

- Ejecta microjets are micron-scale jets of material comprised of particles that travel at velocities exceeding several km/s and as such, offer a potential experimental methodology to study high-speed particle collision dynamics
- The interactions of high-speed particle collisions are broadly relevant to fields ranging from pebble accretion in planetary formation to cold-spray welding, chemically reactive sprays, and cloud interaction dynamics
- Because of the difficulty of generating high speed flows of particles, experimental observations of interaction dynamics are sparse

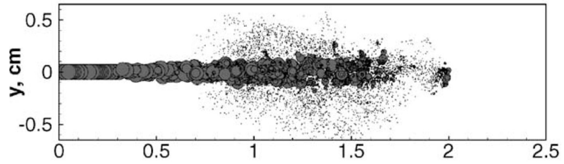
See HEDS seminar on July 29th!



Veysset et al. Nat Comm. (2018)

NASA JPL/Caltech

Sarychev Volcano from ISS



Apte et al. IJMF (2003).

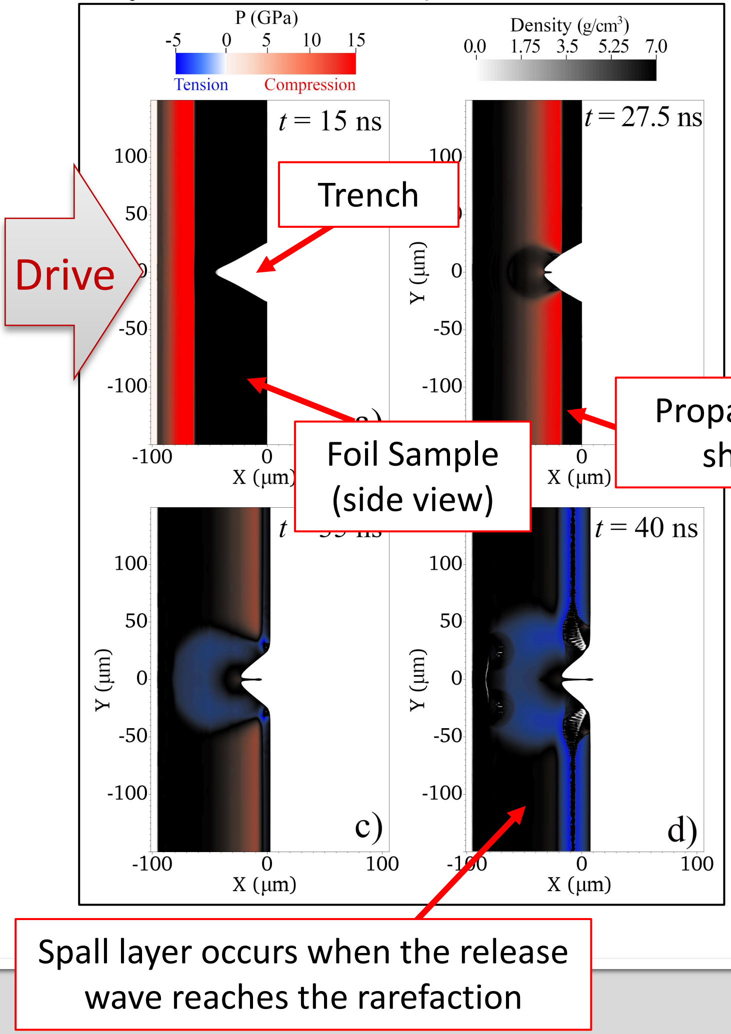
Ejecta microjets are generated by shock waves traveling through materials and interacting with surface features upon release, generating jets of material traveling at several kilometers per second

- Generation mechanisms and jet characteristics vary as a function of shock pressure

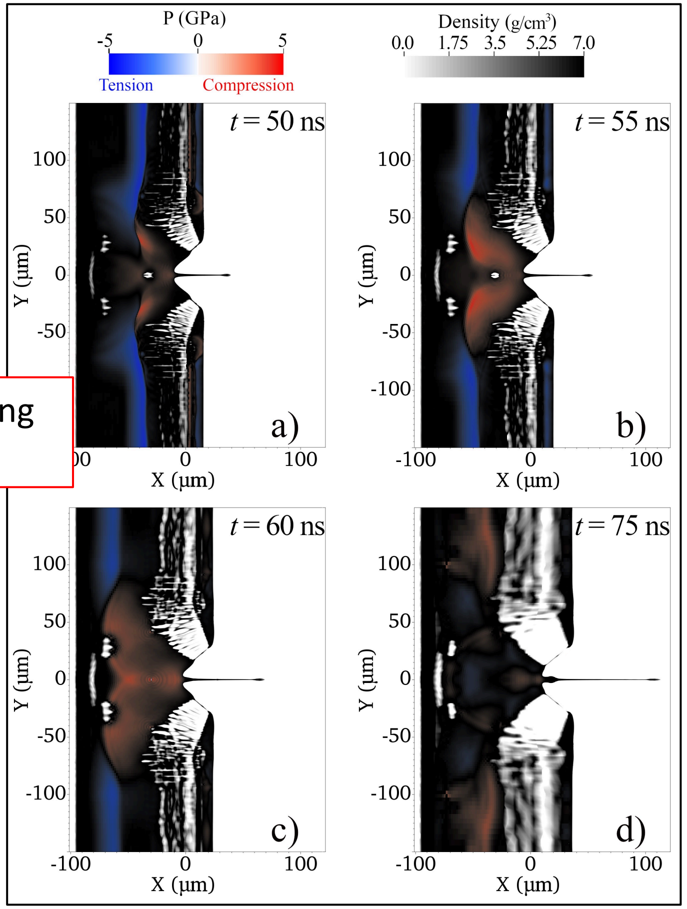
- For the case of tin that is solid-upon-release, the microjet is formed by the release of material and interaction of compression waves
  - By the time the sock wave reaches the surface, the material around the groove is under tension
  - When the release wave reaches the rarefaction, the material spalls
  - Coalescence of compression waves generated by the spallation results in a follow-up jet of higher density material

- In the case of liquid-upon-shock, the material in and behind the jet is melted
  - No material is under tension and no compression waves are launched back into the sample

Early Jet Evolution (15 GPa Release)



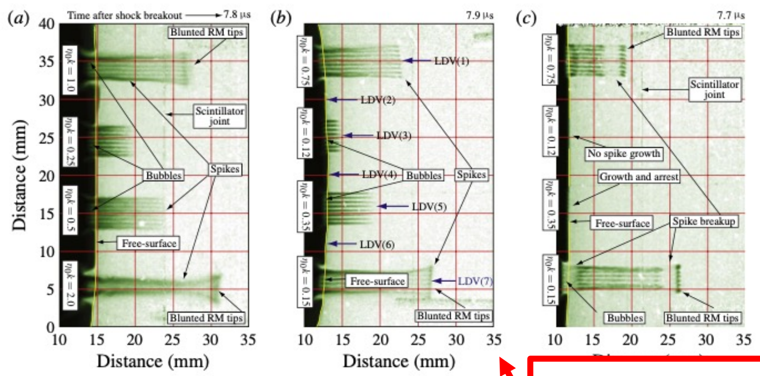
Late Jet Evolution (15 GPa Release)



Mackay et al. JAP 2020

Many experiments have been performed to understand ejecta generation as a function of drive conditions, experimental geometry, and sample material

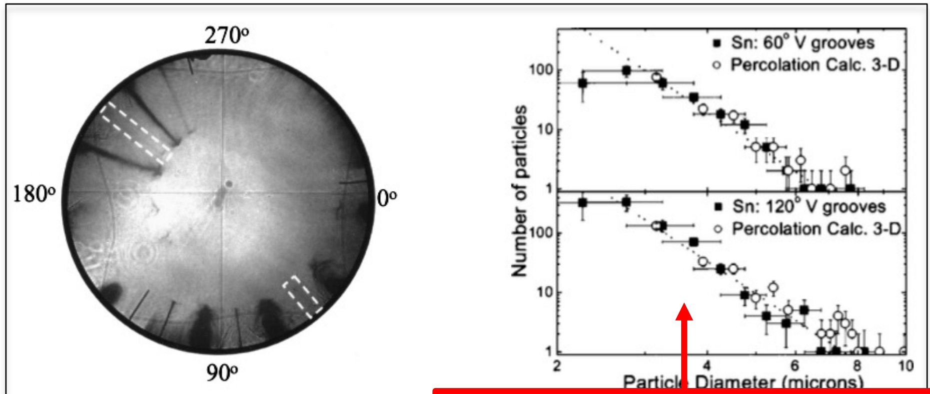
Proton Radiography and PDV to Characterize Areal Mass, Total Mass, and Velocities



Buttler et al. J. Fluid Mech 2012

Development of RMI-based models

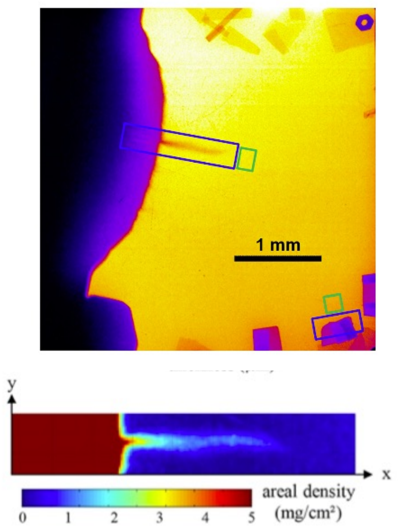
Holography Measurements of Particle Size Distributions



. Sorenson et al. JAP 2002

Particle sizes follow log normal distribution with peak ~1 µm

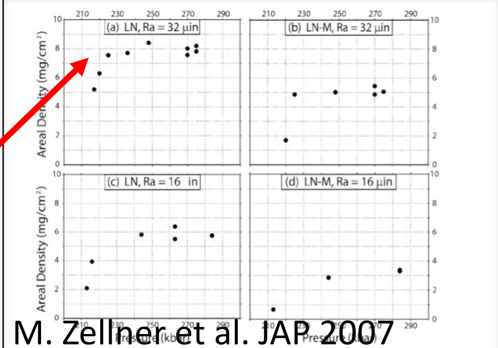
Radiography to Measure Areal Density and Velocity



de Resseguier et al. JAP 2018

First demonstrations of laser-driven platforms

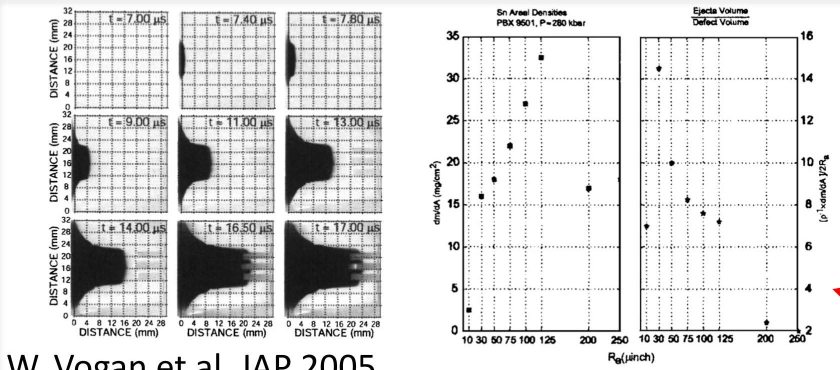
PDV and Pins to Understand Effects of Shock Pressure



M. Zellner et al. JAP 2007

Density of jets increases with increasing pressure and increasing perturbation depth

Shadowgraphy, Radiography, and Piezoelectric Pins to Understand Effects of Surface Characteristics

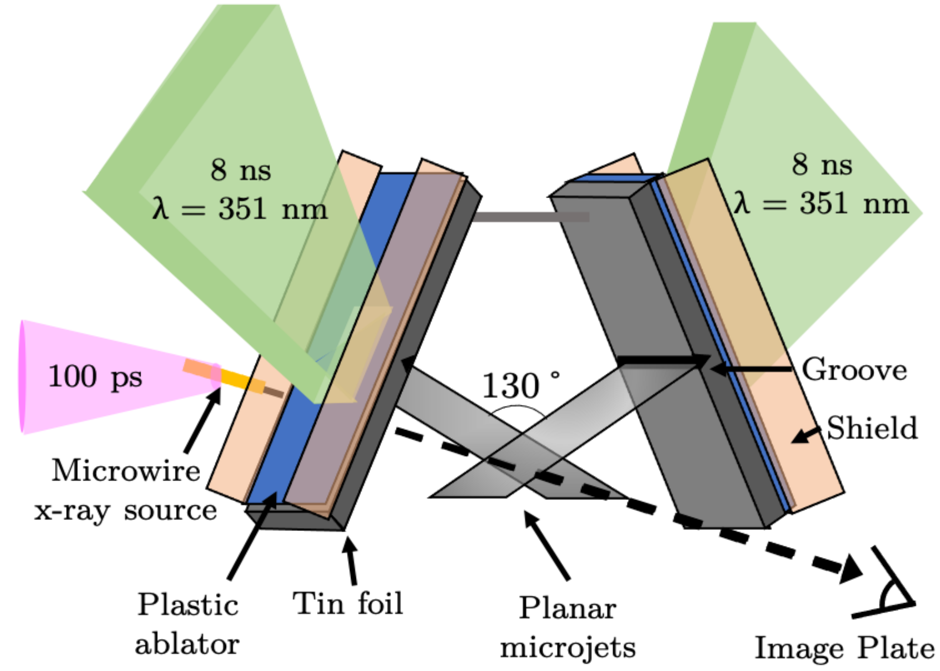


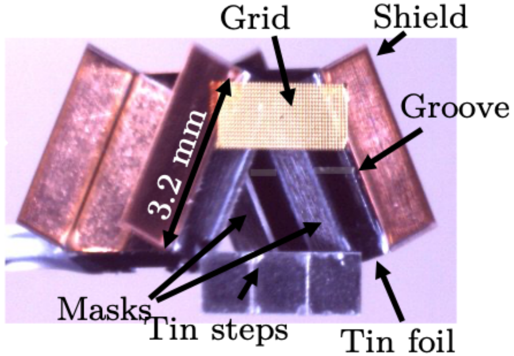
W. Vogan et al. JAP 2005

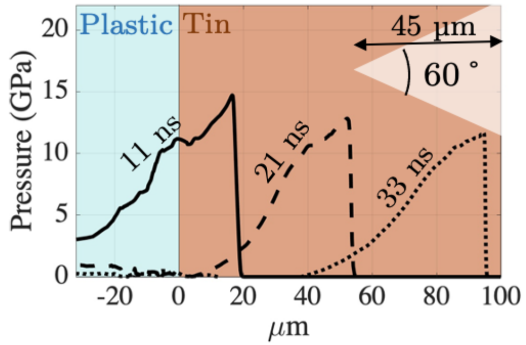
Jet characteristics vary with groove depth and opening angle

We have developed platforms for the OMEGA EP laser to study tin ejecta microjet interactions

- We want to understand how jet characteristics affect jet interactions
- Samples consist of diamond-turned tin foils with 60˚ angular trenches carved into the rear surfaces
  - We use tin because many material phases are available with laser drives (ranging from solid on release to melted upon shock)
- Long-pulse lasers drive shocks through the tin to generate planar microjets
- We use x-ray radiography to characterize the jets before and after interaction
  - X-rays are generated with the EP short pulse beam incident on a microwire flag
  - Radiographs are captured using an image-plate diagnostic

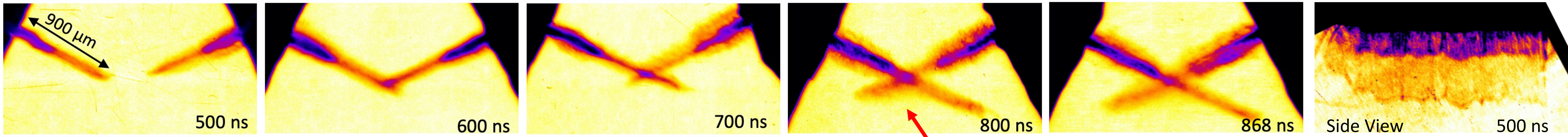






We captured the first “movies” of microjet interactions, capturing the collisional behavior

Tin shock pressure before release: 11.7 GPa



Jet velocity: 2.2 km/s
Free surface velocity: 0.6 km/s

Microjets appear to pass through each other

Saunders et al. Submitted to PRL

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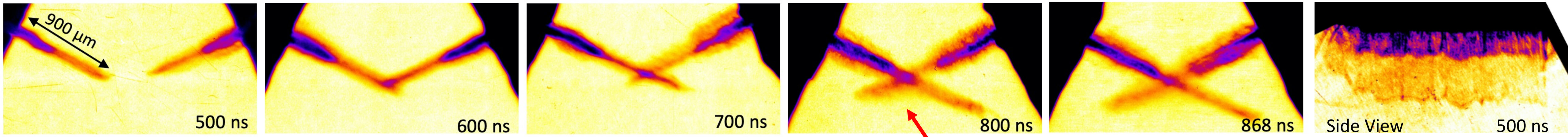

Jet velocity: 2.2 km/s
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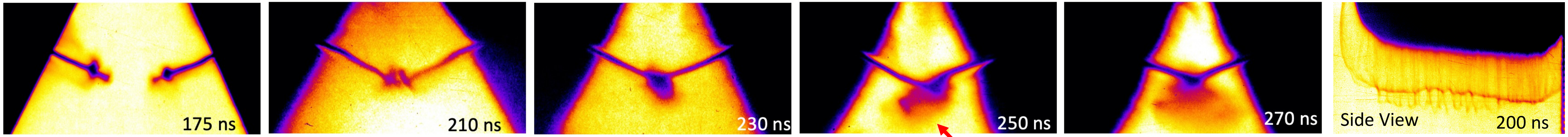
Microjets appear to pass through each other

Tin shock pressure before release: 116.0 GPa



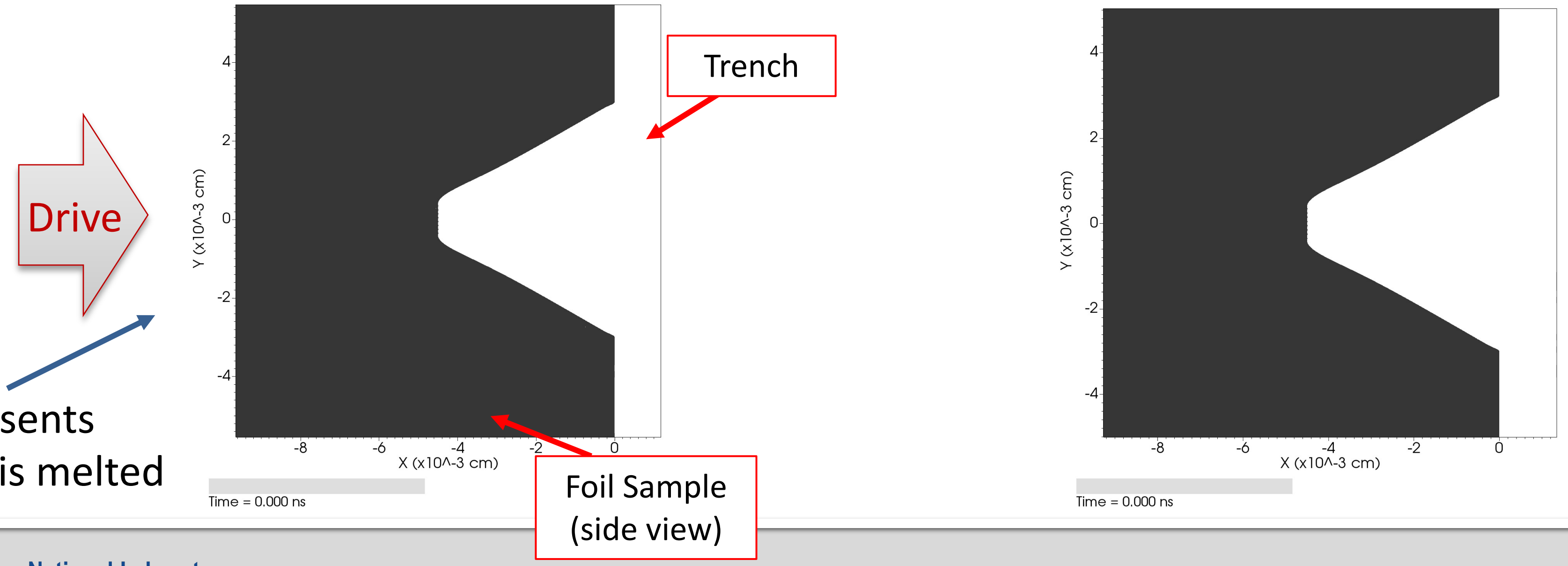
Jet velocity: 6.5 km/s
Free surface velocity: 3.9 km/s

Jets interact to form a cloud of lower-density material

Saunders et al. Submitted to PRL

Hydrodynamics simulations suggest the difference in jet appearance we observe results from target geometry and material effects

- In our case, the angular trenches are more trapezoidal than triangular and have an 8 μm flat region on the bottom
- Microjets release from both of the sharp corner regions and coalesce in the center
- Material strength holds the material together in the case of the 11.7 GPa drive, but the melted material in the 116.0 GPa case forms a bulbous region at the front of the jet

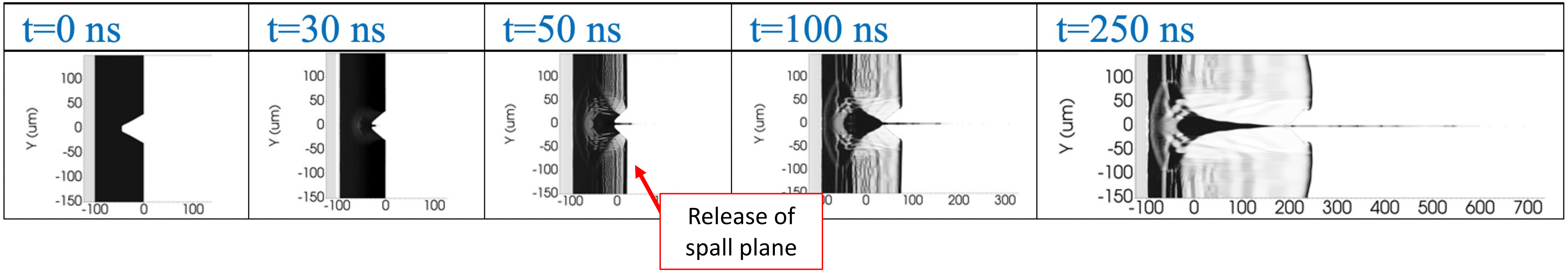


Red represents material that is melted

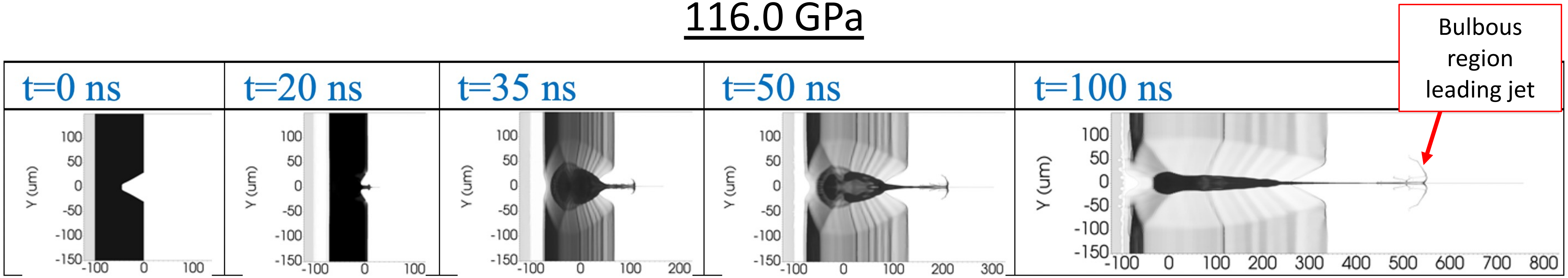
Simulations by K. Mackay

Hydrodynamics simulations suggest the difference in jet appearance we observe results from target geometry and material effects

11.7 GPa



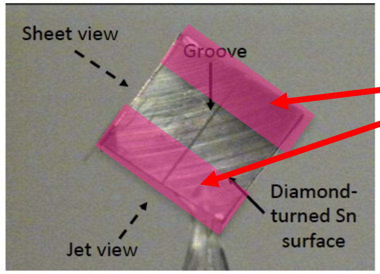
116.0 GPa



Simulations by K. Mackay

We optimized the platform to characterize density and volume fraction of the microjets

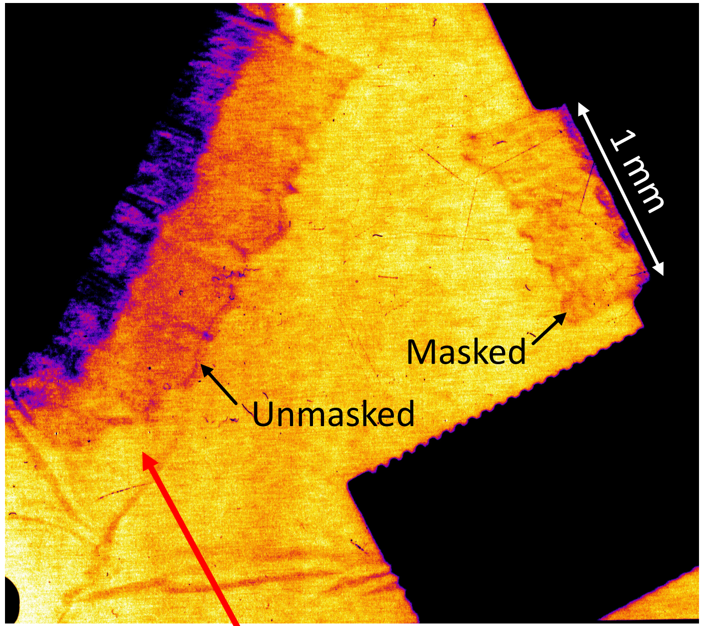
- Radiography characterizes areal density, which can be misconstrued in these experiments due to the non-planar nature of the drive and jetting material
  - $I = I_0 e^{-\mu\rho r}$
- We offset thick tantalum masks on the rear surfaces of the tin to limit the amount of material that propagates to the interaction region such that we know the r in the exponent



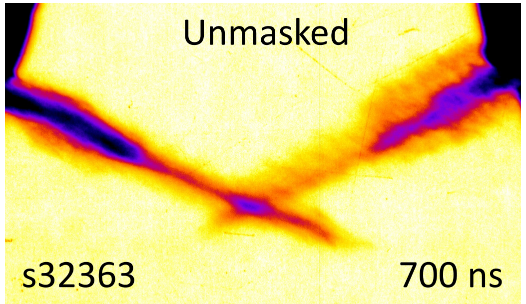
Masks

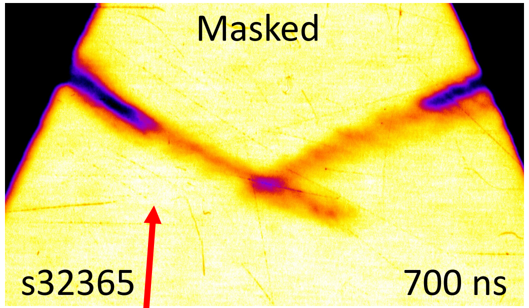
- A side-by-side comparison of shots with and without the masks show the efficacy of masks in improving data quality

Sheet-view Image of Jets



Jet-view in unmasked targets sees through regions affected by drive non-planarity

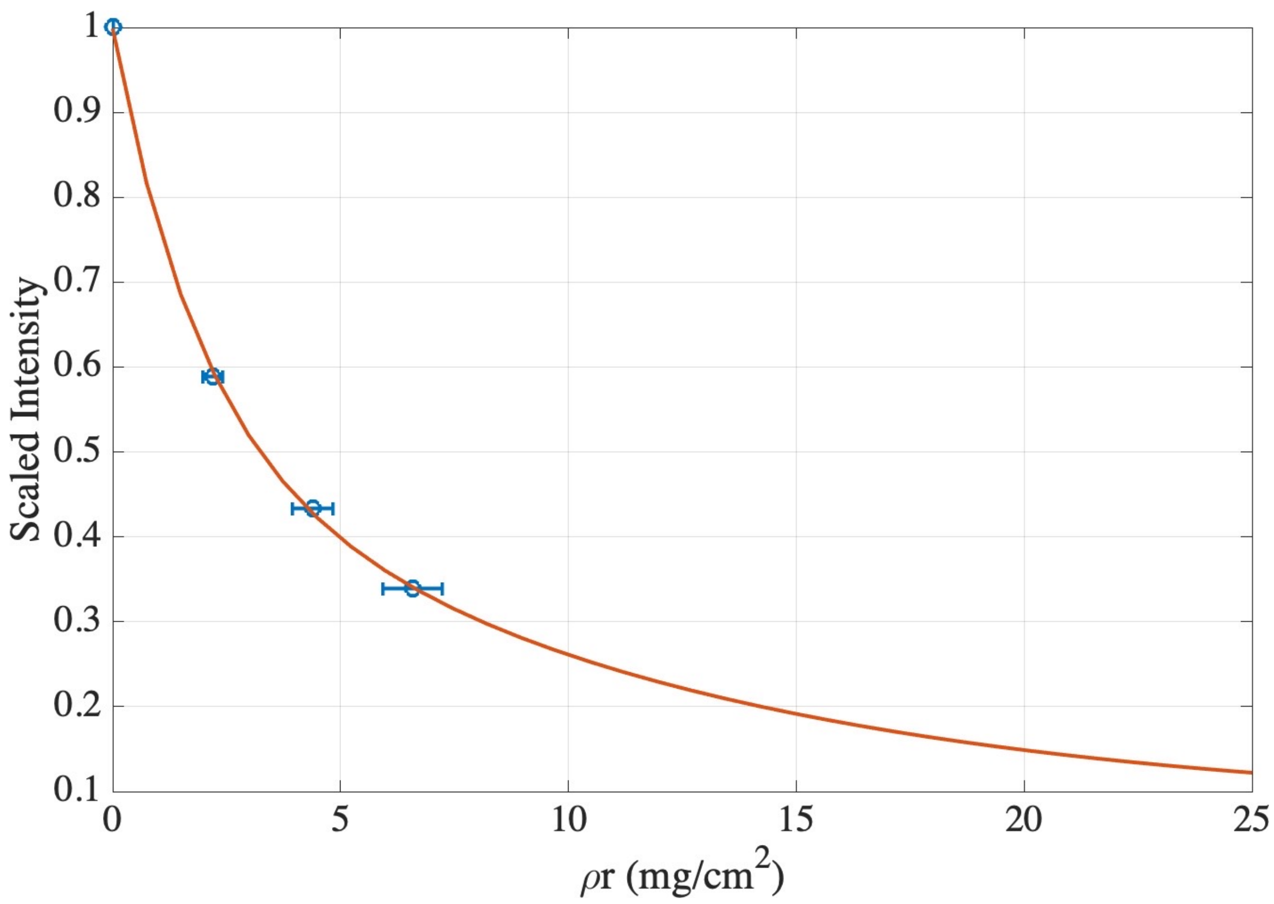




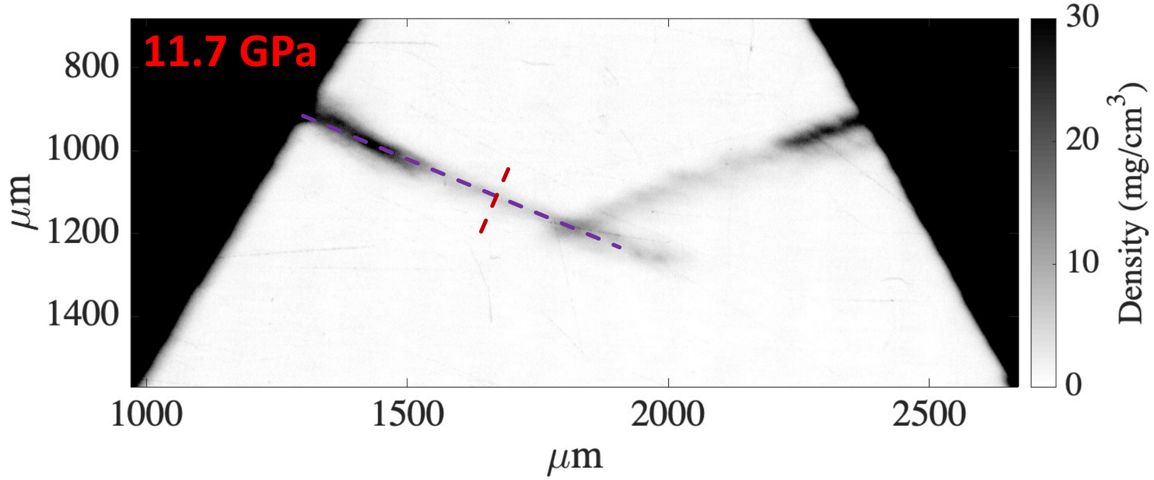
Masks noticeably improve data quality

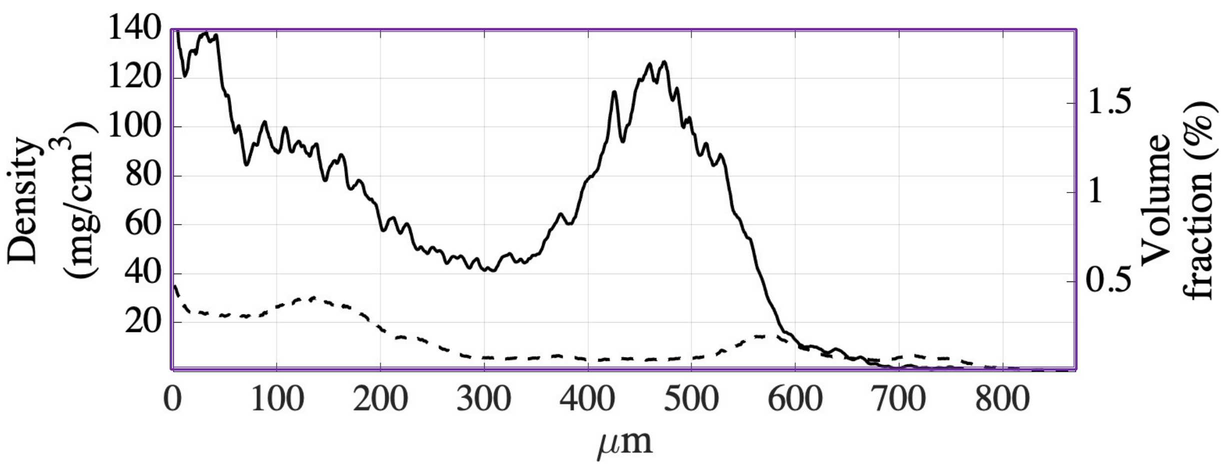
We use tin steps of variable thicknesses to calibrate our radiography data such that no absolute spectral data is needed

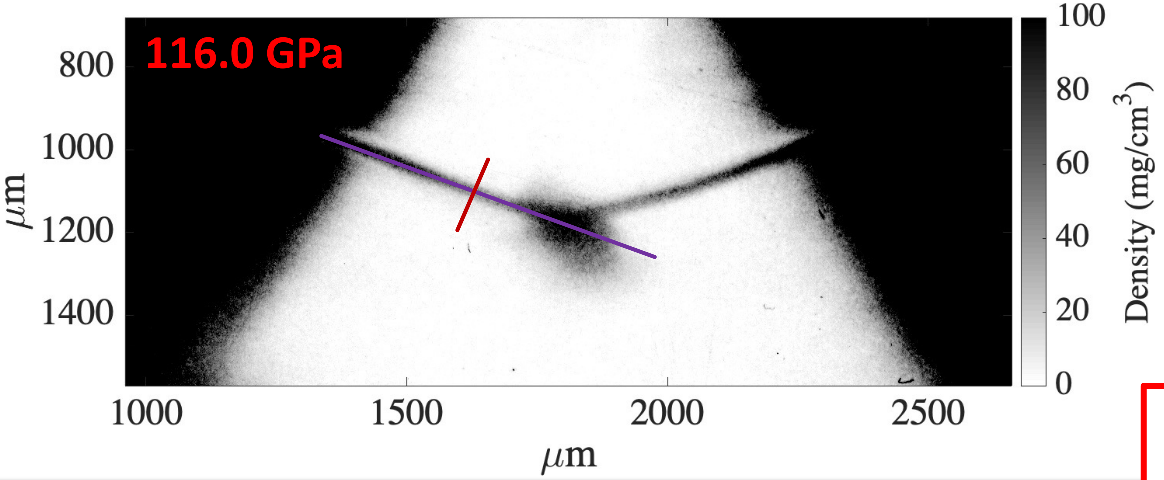
- We have three steps of tin: 3, 6, and 9 µm
- We fit the intensity versus known areal density to the curve:
  - $I = A(e^{-\mu_1 \rho r} + e^{-\mu_2 \rho r}) + I_0$
  - The short pulse laser incident on a microwire generates a non-mono-energetic spectrum, so we need to account for multiple x-ray wavelengths
- We then apply the transformation to our data to obtain density
- Uncertainties suggest a 19% error in density reconstruction using this method

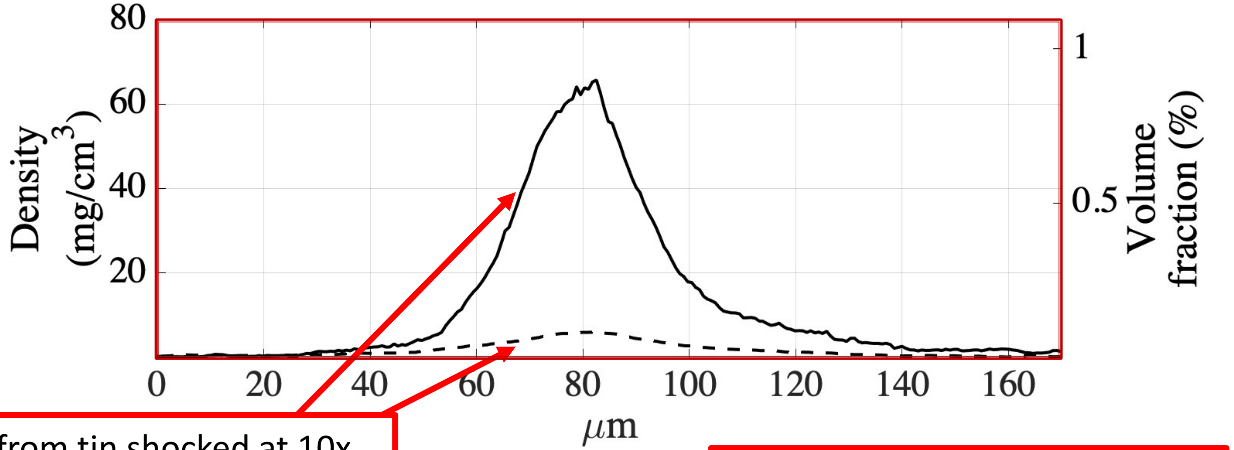


An analysis of the data at two different tin release pressures shows differences in microjet morphology







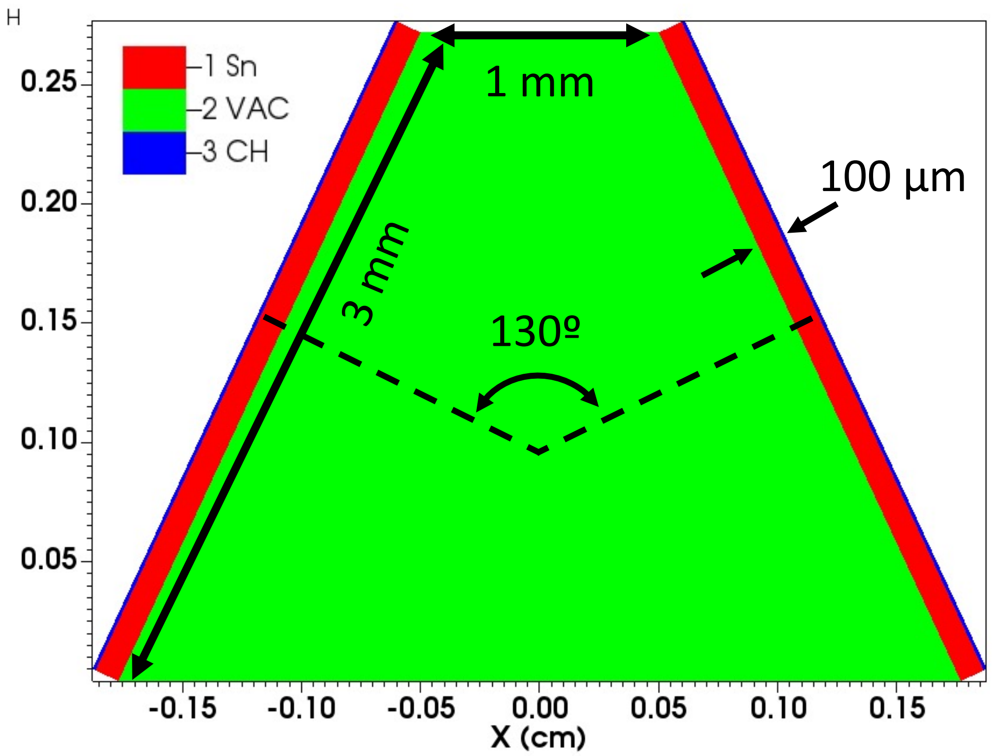


Jets from tin shocked at 10x higher pressures have densities and volume fractions 6x higher

$$\text{Volume Fraction} = \rho_{\text{jet}}/\rho_{\text{Sn}}$$

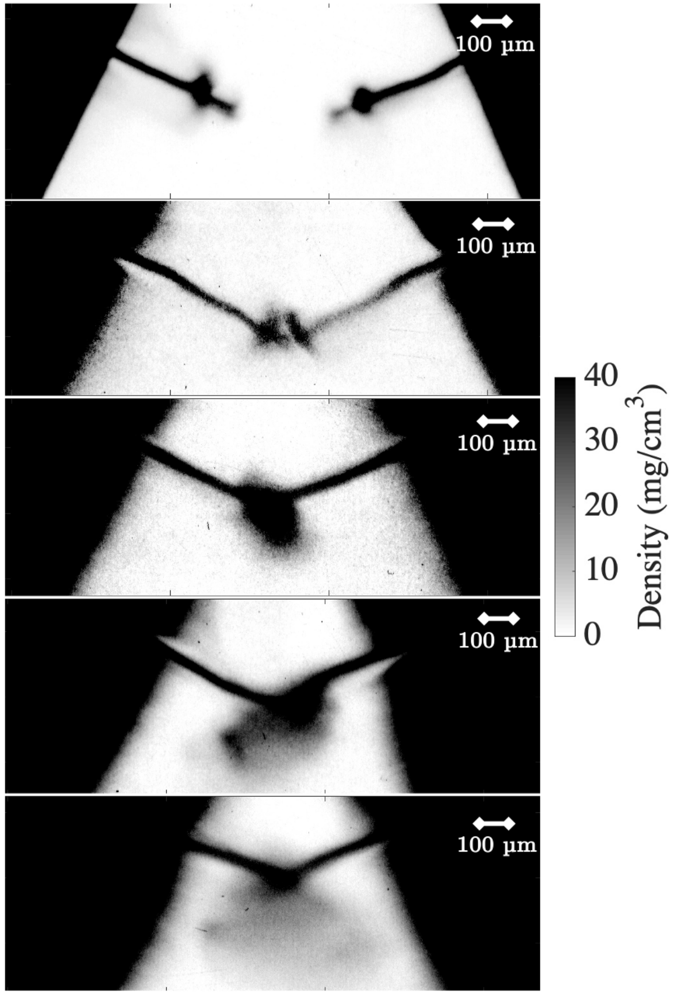
We performed simulations to model the interaction of the jets from tin release pressures of 116.0 GPa

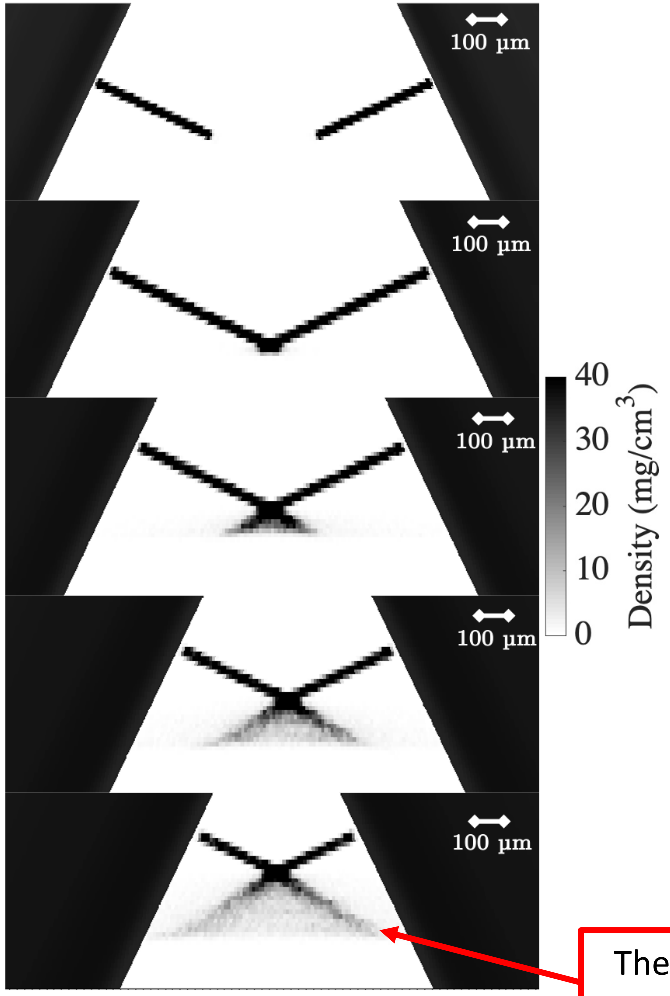
- In practice, it is not feasible to maintain computational resolution necessary to resolve all the post-breakup material in the jets, so a simpler model is needed to predict behavior of interactions
- We use a multiphase particle-in-cell approach that solves 2-way coupled transport equations for Lagrangian point particles in an Eulerian (or ALE) carrier fluid.
- Collision model from the Kiva Code (O'Rourke 1987) assumes hard spherae, elastic scattering, and a probabilistic treatment of collision likelihood
- We inject particles and assume a power law distribution for particle sizes comprising each microjet (consistent with measurements made in the literature) and a linear velocity distribution, consistent with experimental observations and hydrodynamics simulation results



From Brandon Morgan

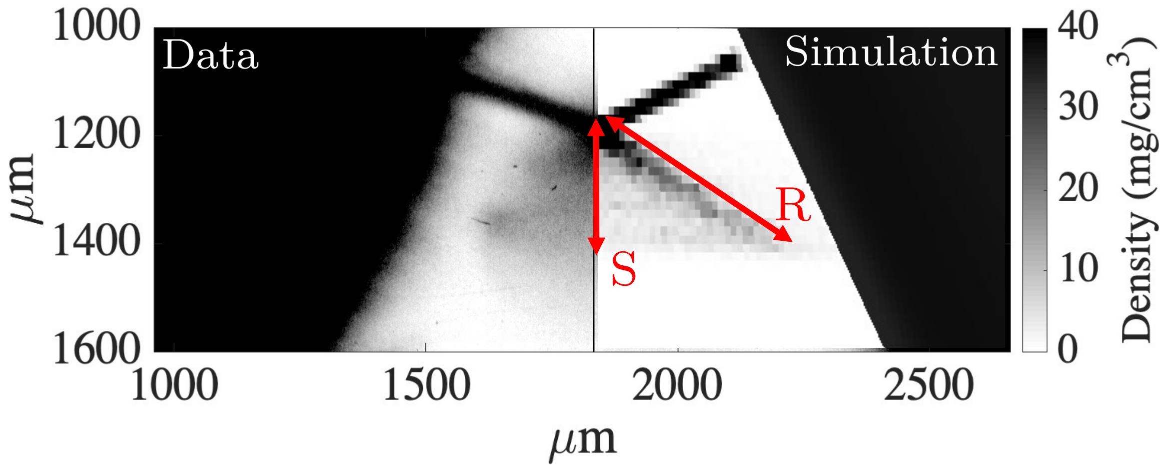
We find that the vertical spread of mass due to the collisions is not well matched by the simulations

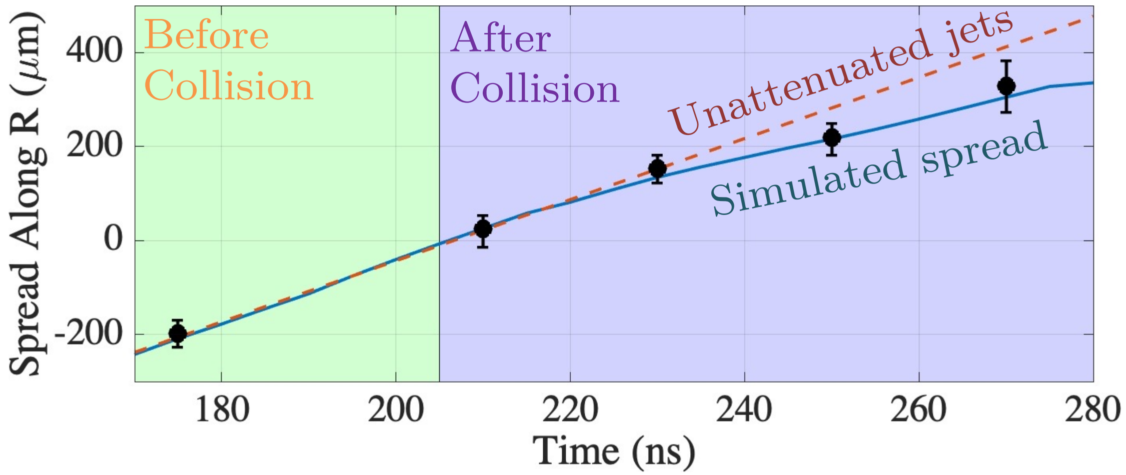


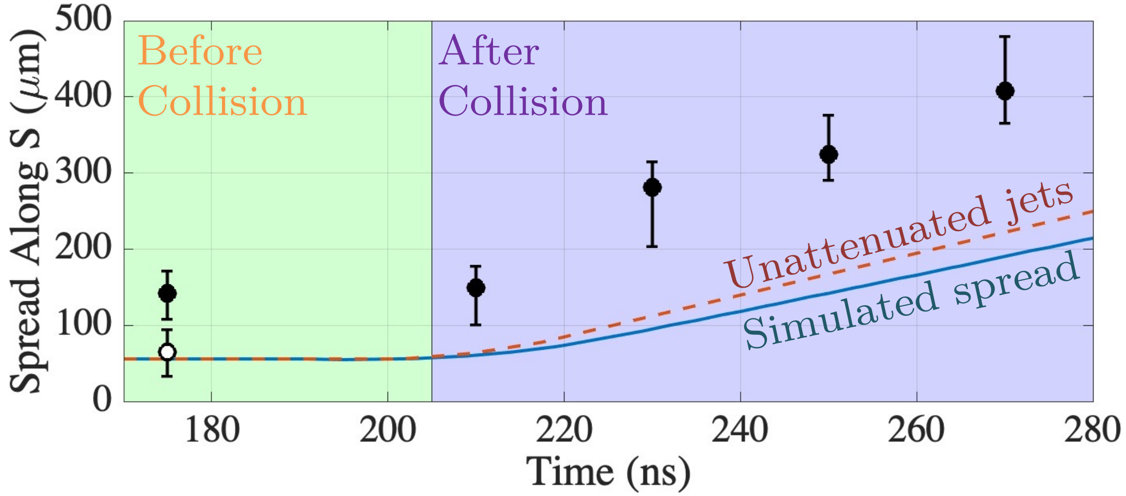


The full extent of the cloud is not captured

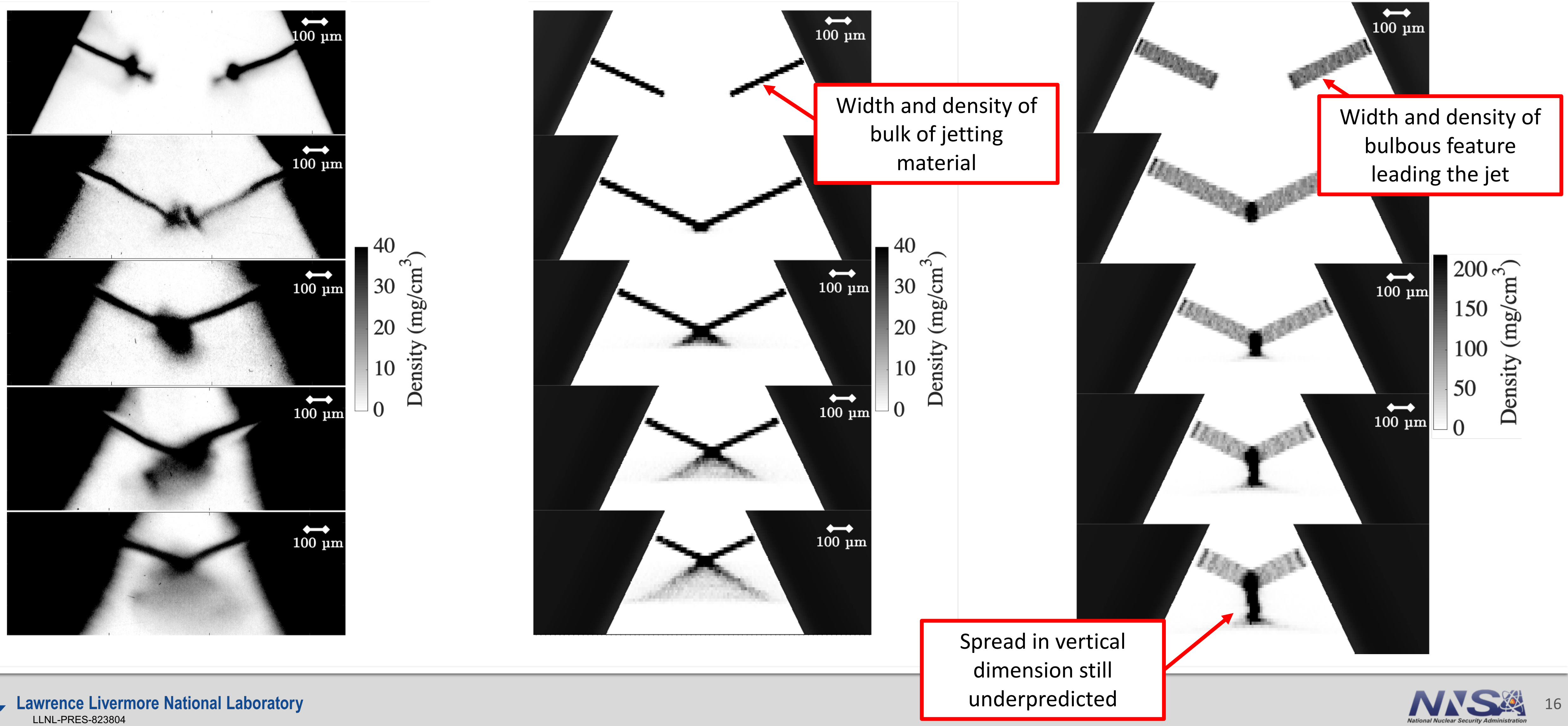
However, the simulations do capture the spread in the direction of jet propagation, suggesting geometric effects may be at play





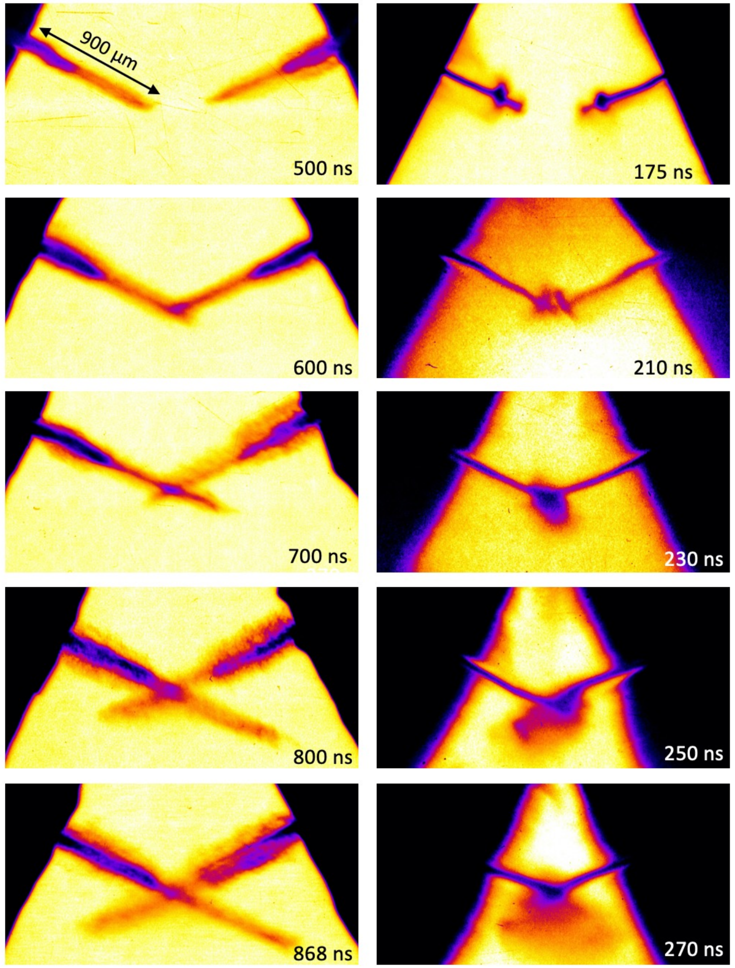


Simulations that account for jet inhomogeneities also fail to capture the observed behavior, suggesting new modeling methodologies are needed



More work is needed to understand the physics governing collisional behavior and the modeling complexities required to capture interaction effects

- Collisional behavior may differ across different tin release pressures due a variety of reasons
  - Particle breakup/agglomeration
  - Elasticity
  - Material phase
  - Particle size distributions
  - Jet volume fraction
- Experiments are underway and proposed to investigate each of these effects independently
- Other experimental facilities might provide different types of measurement capabilities to help us to resolve modeling uncertainties



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