SAND2020-10776PE

Experiments and Modeling for Hypersonic Weather Environments

October 7, 2020

Steven Beresh

Aerosciences Department

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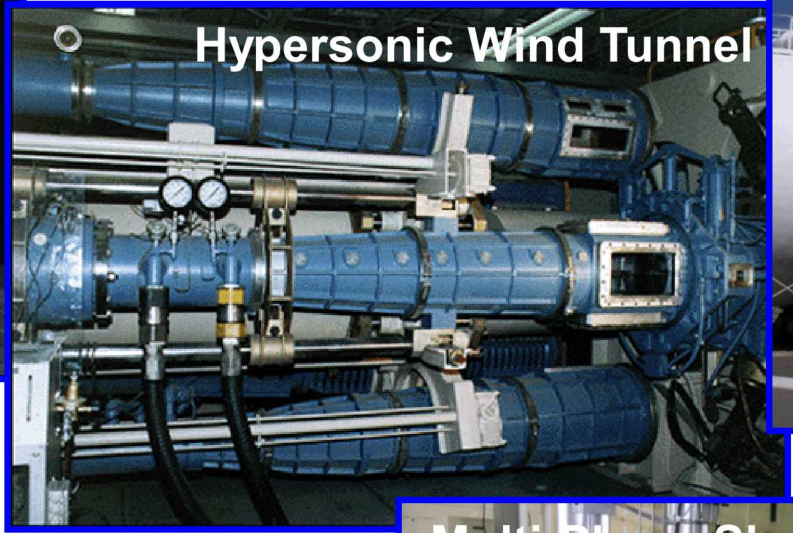
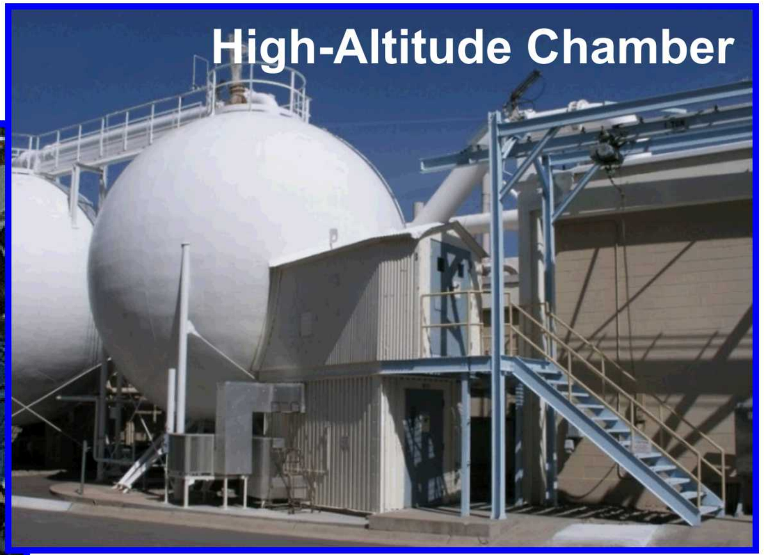
Experimental Aerosciences Facility





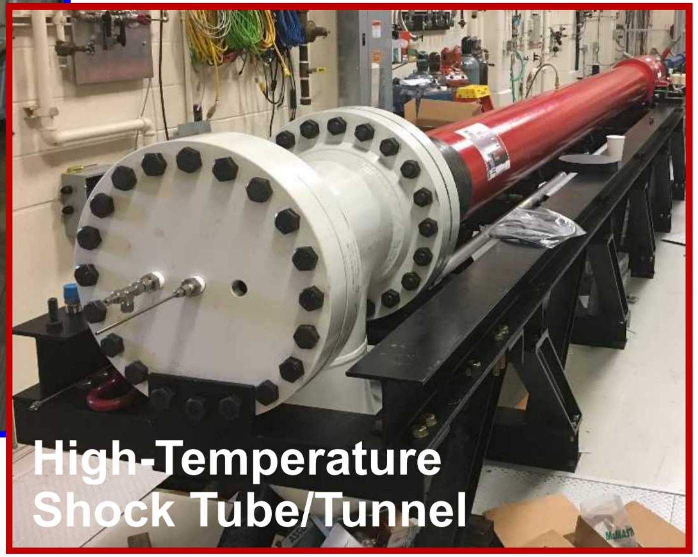
Trisonic Wind Tunnel (TWT)
- Mach 0.5 – 3
- Gravity bombs, missiles

Hypersonic Wind Tunnel (HWT)
- Mach 5, 8, 14
- Re-entry vehicles, future systems

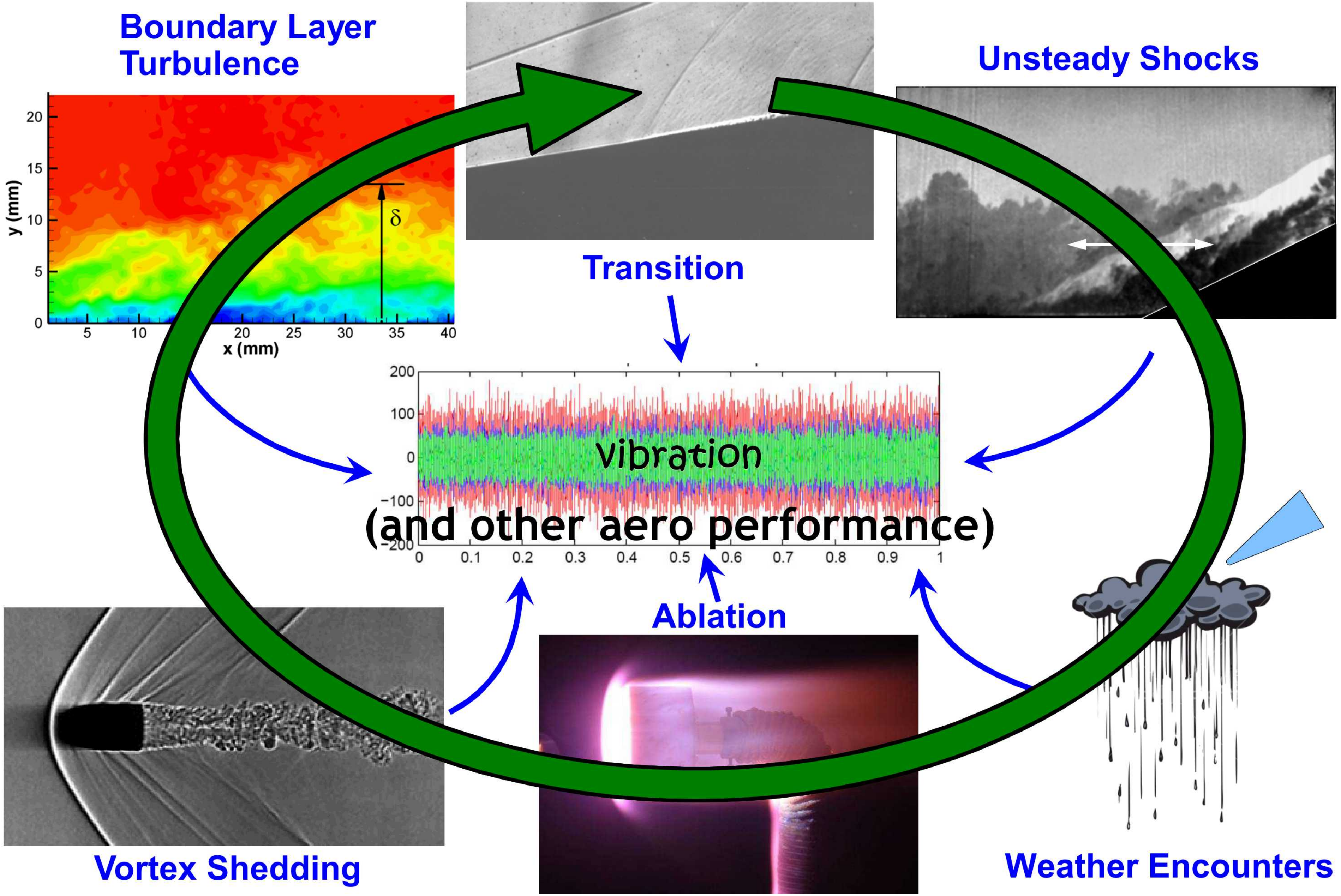
High-Altitude Chamber (HAC)
- Satellite components

Multi-Phase Shock Tube (MST)
- Explosives research

High-Temperature Shock Tube (HST)
- Soon to be a Mach 8 Shock Tunnel…



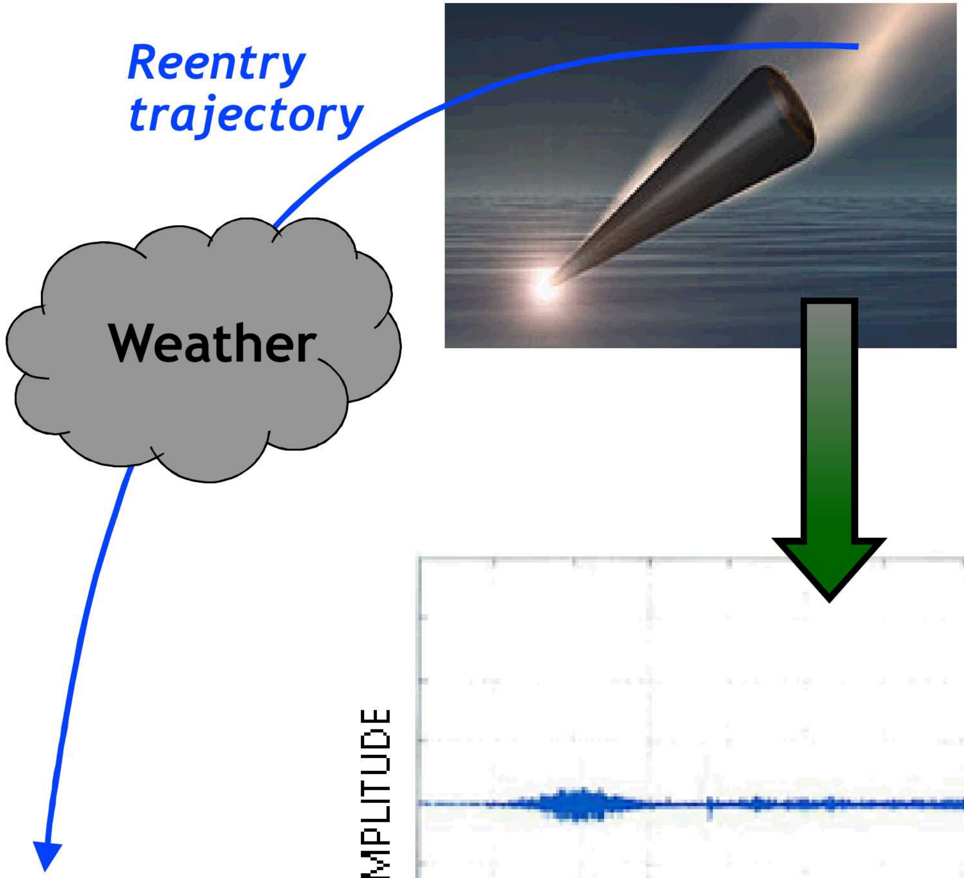
Combined Environments in Aero Testing



Simulating Hypersonic Weather Encounters

Hypersonic vehicles must fly through adverse weather.

Causes significant effects aerodynamically and structurally.

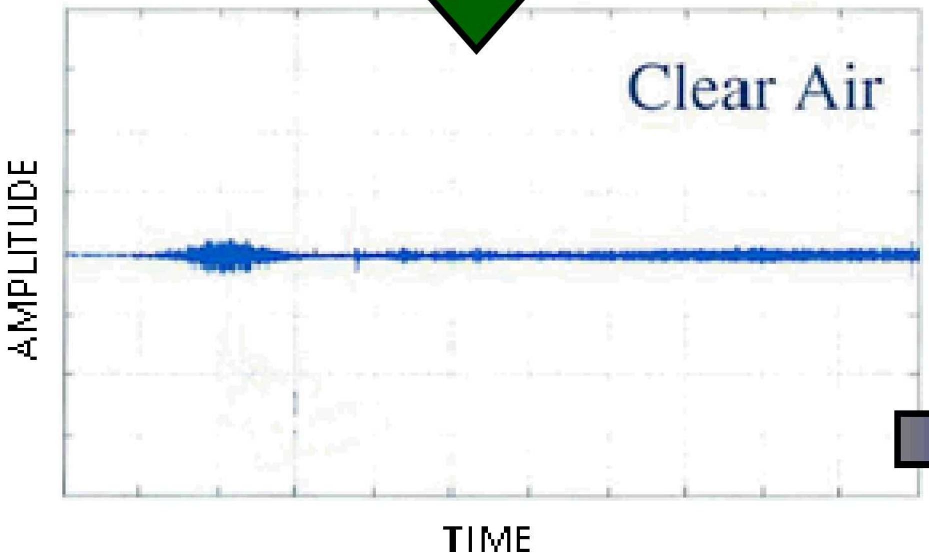


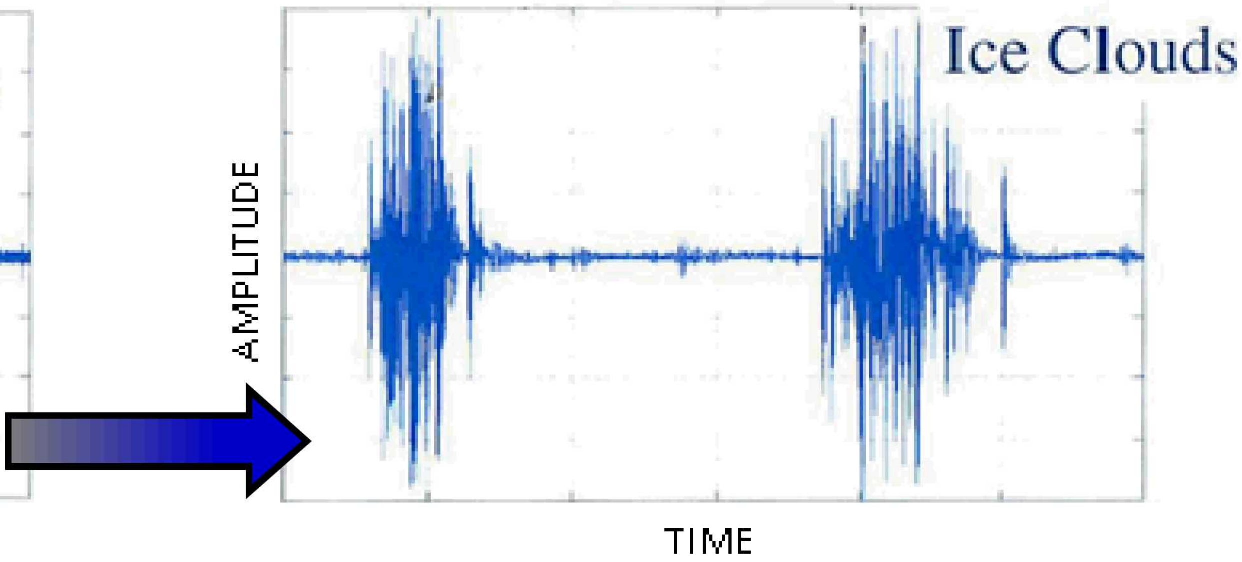
Erosive flight environments are a serious threat to the operability and survivability of hypersonic systems.

Predictive codes are designed for ballistic flight, and may be poorly suited for new applications.

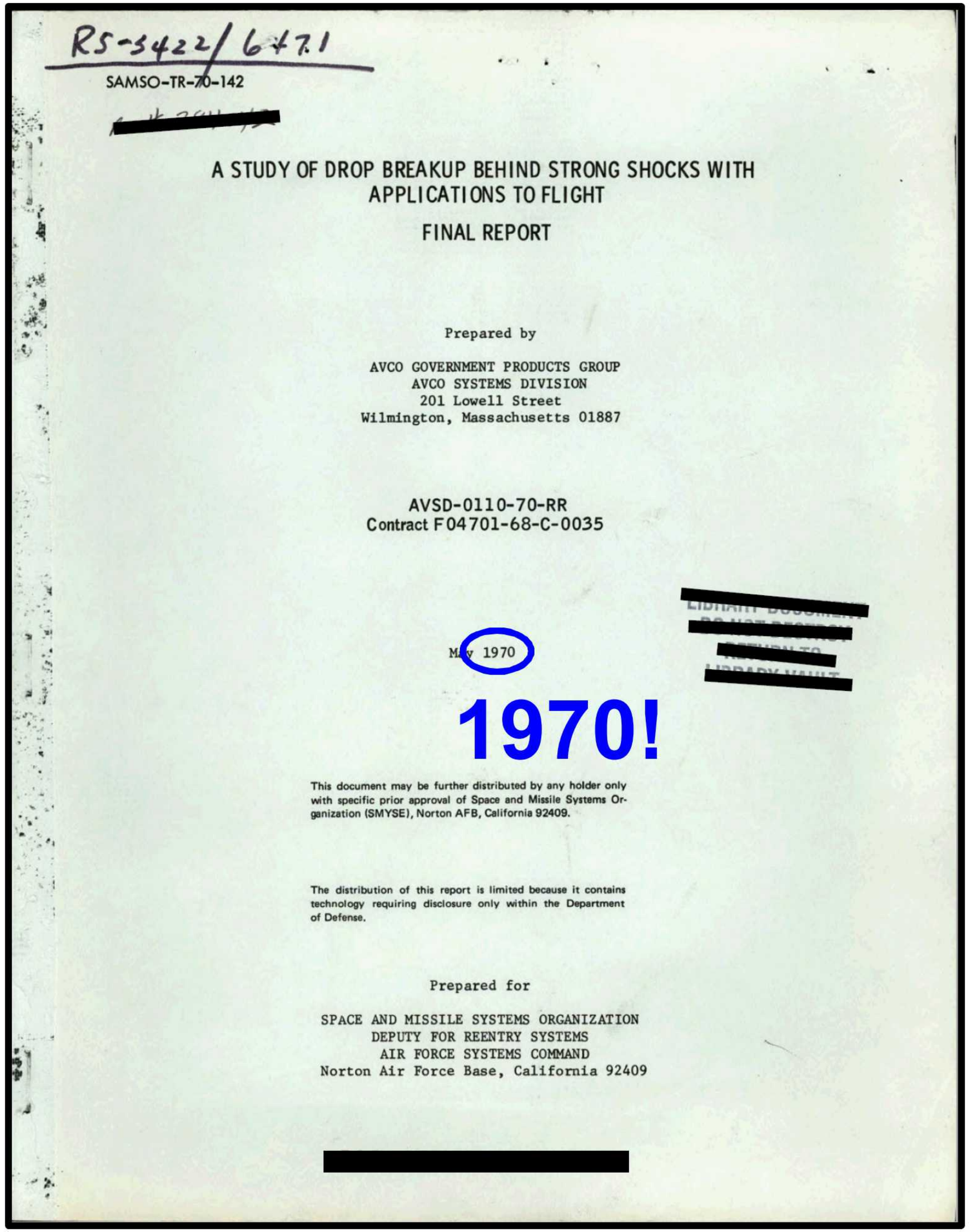
Data are extremely limited and qualification is difficult.

Sandia perspective is focused on vibration loading and structural response.





Our current model is little more than these historical models:



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A STUDY OF DROP BREAKUP BEHIND STRONG SHOCKS WITH APPLICATIONS TO FLIGHT

FINAL REPORT

Prepared by

AVCO GOVERNMENT PRODUCTS GROUP
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AVSD-0110-70-RR
Contract F04701-68-C-0035

[redacted]

May 1970

1970!

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Prepared for

SPACE AND MISSILE SYSTEMS ORGANIZATION
DEPUTY FOR REENTRY SYSTEMS
AIR FORCE SYSTEMS COMMAND
Norton Air Force Base, California 92409

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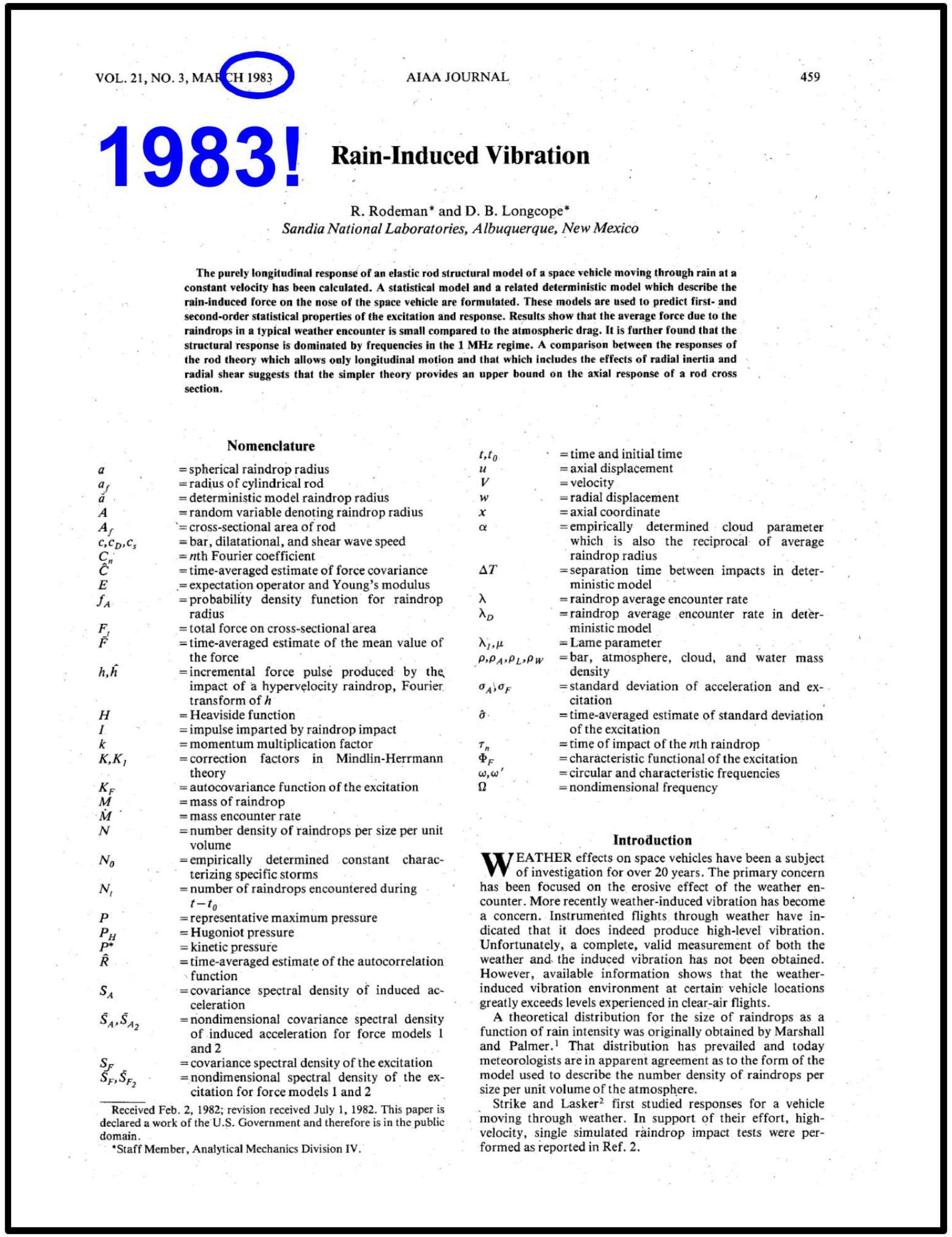


1983!

Rain-Induced Vibration

R. Rodeman* and D. B. Longcope*
Sandia National Laboratories, Albuquerque, New Mexico

The purely longitudinal response of an elastic rod structural model of a space vehicle moving through rain at a constant velocity has been calculated. A statistical model and a related deterministic model which describe the rain-induced force on the nose of the space vehicle are formulated. These models are used to predict first- and second-order statistical properties of the excitation and response. Results show that the average force due to the raindrops in a typical weather encounter is small compared to the atmospheric drag. It is further found that the structural response is dominated by frequencies in the 1 MHz regime. A comparison between the responses of the rod theory which allows only longitudinal motion and that which includes the effects of radial inertia and radial shear suggests that the simpler theory provides an upper bound on the axial response of a rod cross section.

Nomenclature

a	= spherical raindrop radius
a_f	= radius of cylindrical rod
$\bar{a}$	= deterministic model raindrop radius
A	= random variable denoting raindrop radius
A_f	= cross-sectional area of rod
c, c_D, c_s	= bar, dilatational, and shear wave speed
C_n	= nth Fourier coefficient
$\hat{C}$	= time-averaged estimate of force covariance
E	= expectation operator and Young's modulus
f_A	= probability density function for raindrop radius
F_t	= total force on cross-sectional area
$\hat{F}$	= time-averaged estimate of the mean value of the force
$h, \hat{h}$	= incremental force pulse produced by the impact of a hypervelocity raindrop, Fourier transform of h
H	= Heaviside function
I	= impulse imparted by raindrop impact
k	= momentum multiplication factor
K, K_1	= correction factors in Mindlin-Herrmann theory
K_F	= autocovariance function of the excitation
M	= mass of raindrop
$\dot{M}$	= mass encounter rate
N	= number density of raindrops per size per unit volume
N_0	= empirically determined constant characterizing specific storms
N_t	= number of raindrops encountered during $t - t_0$
P	= representative maximum pressure
P_H	= Hugoniot pressure
P^*	= kinetic pressure
$\hat{R}$	= time-averaged estimate of the autocorrelation function
S_A	= covariance spectral density of induced acceleration
$\bar{S}_A, \bar{S}_{A_2}$	= nondimensional covariance spectral density of induced acceleration for force models 1 and 2
S_F	= covariance spectral density of the excitation
$\bar{S}_F, \bar{S}_{F_2}$	= nondimensional spectral density of the excitation for force models 1 and 2
t, t_0	= time and initial time
u	= axial displacement
V	= velocity
w	= radial displacement
x	= axial coordinate
α	= empirically determined cloud parameter which is also the reciprocal of average raindrop radius
ΔT	= separation time between impacts in deterministic model
λ	= raindrop average encounter rate
λ_D	= raindrop average encounter rate in deterministic model
λ_1, μ	= Lame parameter
$\rho, \rho_A, \rho_L, \rho_W$	= bar, atmosphere, cloud, and water mass density
σ_A, σ_F	= standard deviation of acceleration and excitation
$\hat{\sigma}$	= time-averaged estimate of standard deviation of the excitation
τ_n	= time of impact of the nth raindrop
Φ_F	= characteristic functional of the excitation
ω, ω'	= circular and characteristic frequencies
Ω	= nondimensional frequency

Received Feb. 2, 1982; revision received July 1, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Staff Member, Analytical Mechanics Division IV.

Introduction

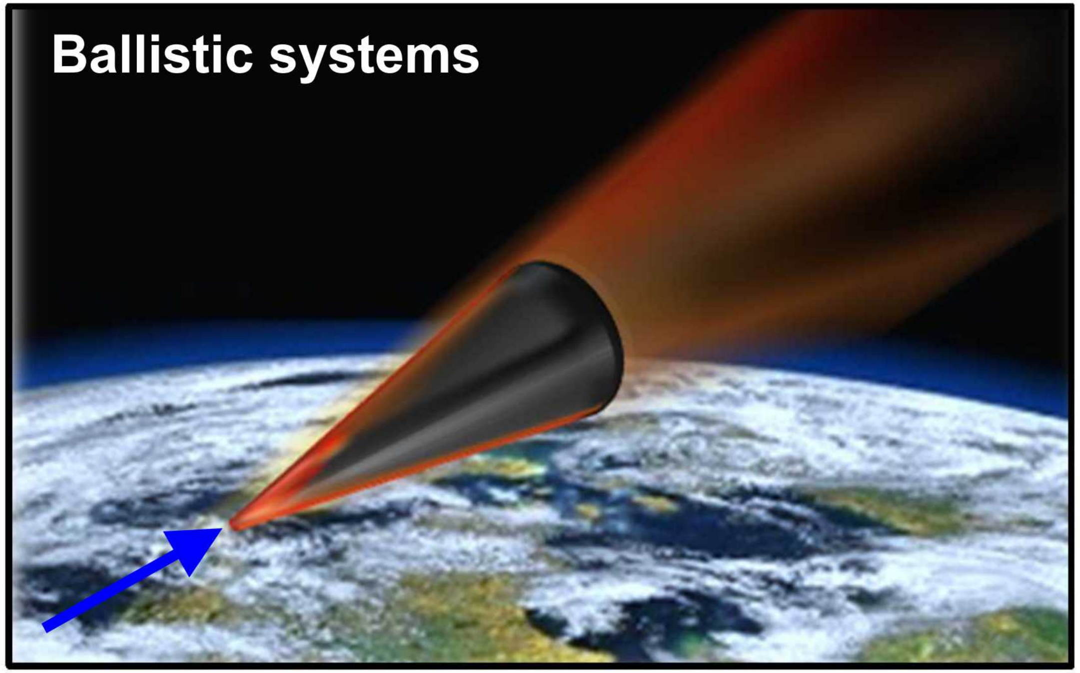
WEATHER effects on space vehicles have been a subject of investigation for over 20 years. The primary concern has been focused on the erosive effect of the weather encounter. More recently weather-induced vibration has become a concern. Instrumented flights through weather have indicated that it does indeed produce high-level vibration. Unfortunately, a complete, valid measurement of both the weather and the induced vibration has not been obtained. However, available information shows that the weather-induced vibration environment at certain vehicle locations greatly exceeds levels experienced in clear-air flights.

A theoretical distribution for the size of raindrops as a function of rain intensity was originally obtained by Marshall and Palmer.[1] That distribution has prevailed and today meteorologists are in apparent agreement as to the form of the model used to describe the number density of raindrops per size per unit volume of the atmosphere.

Strike and Lasker[2] first studied responses for a vehicle moving through weather. In support of their effort, high-velocity, single simulated raindrop impact tests were performed as reported in Ref. 2.

What's missing from this model?

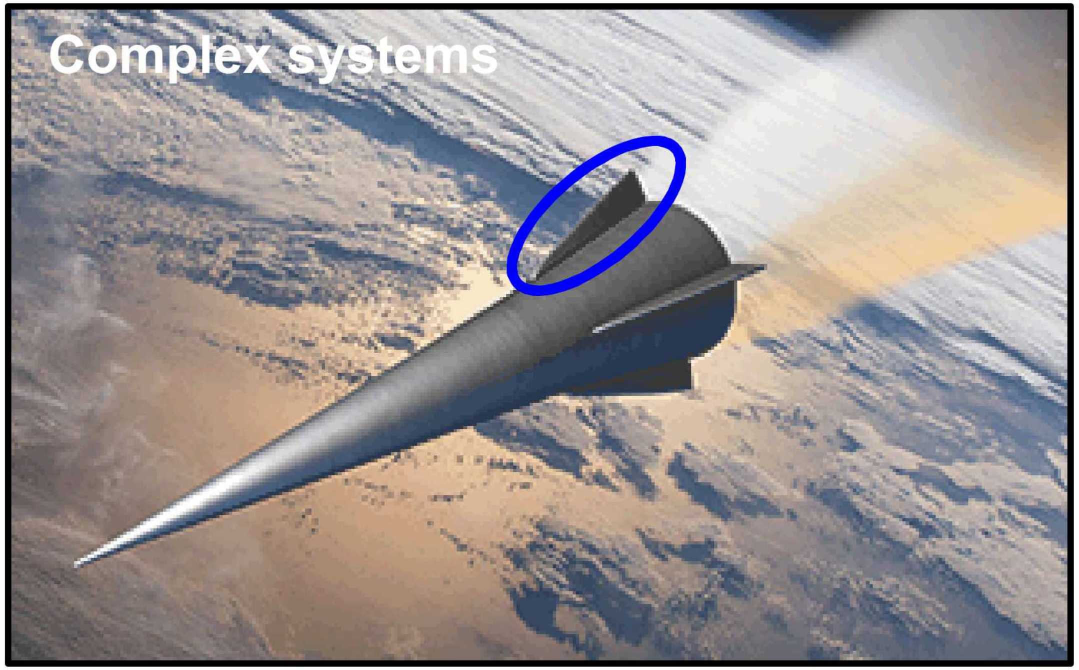
This is a reduced-order model (ROM) informed by flight tests, experiments, and (soon) high-fidelity simulation.



Assumes all particle impacts are at the nose.

This may be a useful assumption for erosion models.

But probably not for vibration.



No model appropriate for aft geometry.

The much longer flow distance invalidates most assumptions of existing models.

What physics do we need to model?

Current predictive models are semi-empirical.

- Based on erosion test data and planar shock experiments.
- Limited validation by flight test.

These existing models are tailored to ballistic vehicles…

…and aim to predict erosion, not aero environment.

We need to predict aero environments for ballistic and complex systems.

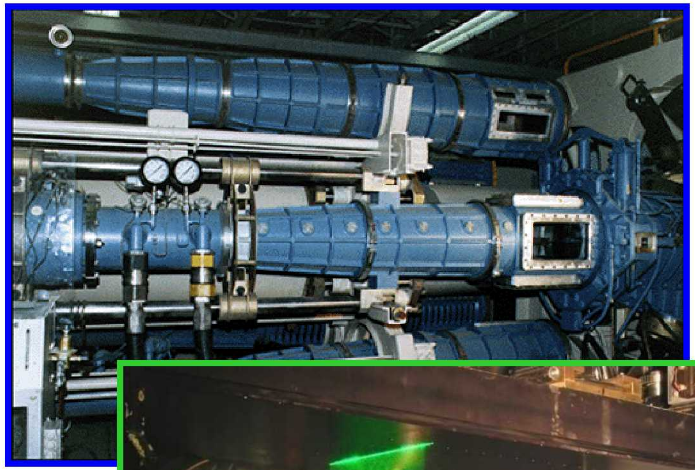
What other physics do we need in a science-based simulation?

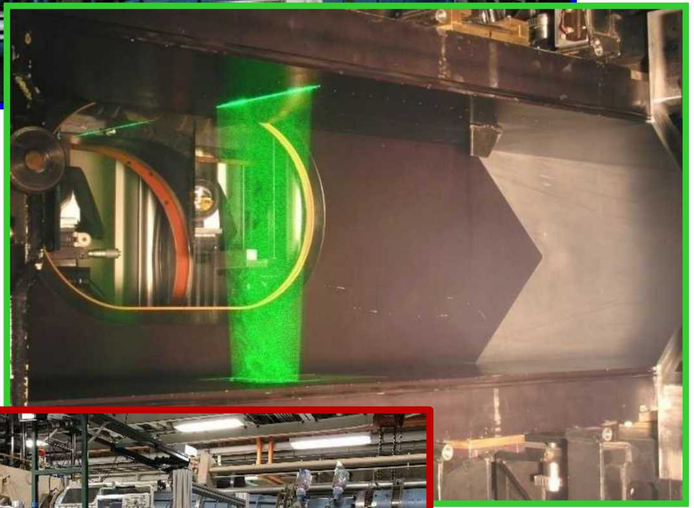
- Move past 1960's era simplifying assumptions.
- Rain droplet deformation and breakup.
- Particulate interaction with the bow shock.
- Particulate interaction with aeroshell materials.
- Effects of material shape change.
- Long convection time to aft geometry.

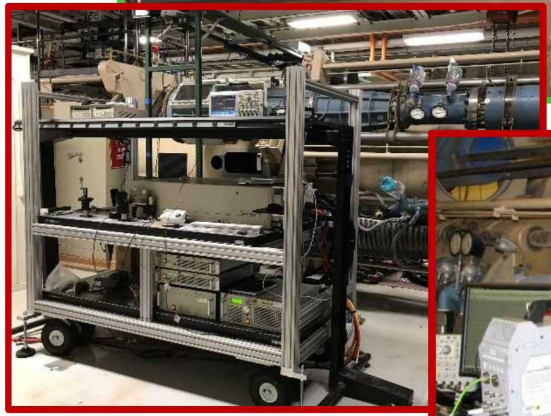
A multi-faceted approach to building a better model:

- **Wind tunnel experiments**
  - Shock/particle interactions; surface pressure and temperature fluctuations
- **Ballistics range experiments**
  - Shock/droplet interactions
- **High-fidelity volume-of-fluid simulations**
  - Shock/droplet interactions
- **Increase fidelity of the ROM that is our ultimate product**
  - Informed by past and future correlations
- **Validation of the ROM**
  - We are searching for appropriate flight test and sled track data (which are not openly available)

Reproducing Weather in Sandia's Hypersonic Wind Tunnel (HWT)







Sandia has considerable experience with laser-based diagnostics that use tiny seed particulates.

We have observed that many failed attempts at seeding look much like weather.

We will leverage existing technology for laser-diagnostics seeding to create a new approach to generating weather environments.

Design will allow us to achieve different weather conditions (*ice, sleet, rain, droplet size/density*).

We have optical diagnostics that can measure particle size distributions and densities of simulated weather.

Instrumented wind tunnel models can directly measure pressure and temperature effects of weather.

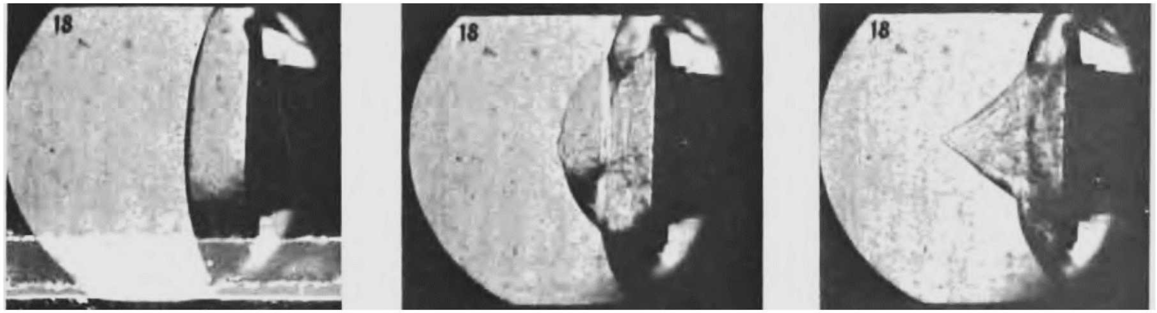
How does weather change the aerodynamic environment?

What can we learn in HWT?

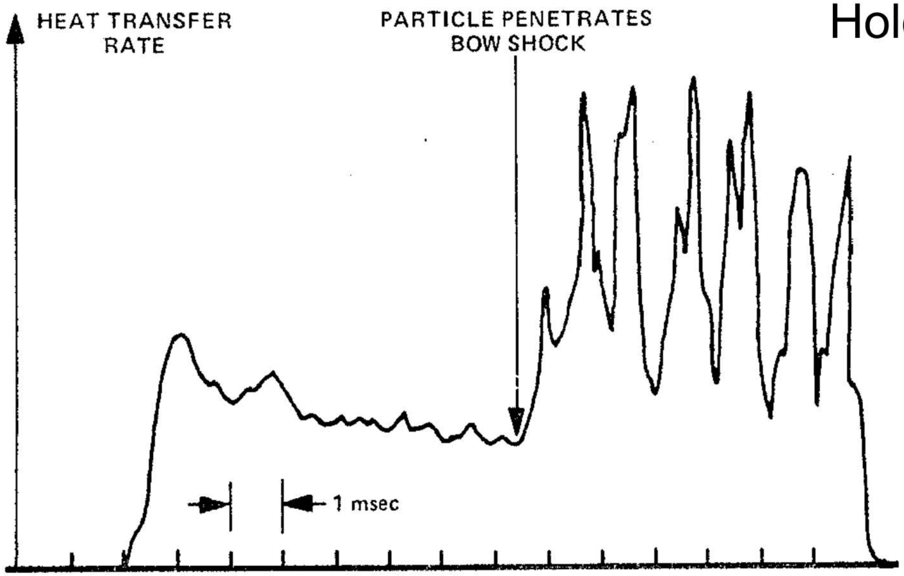
Wind tunnels reproduce the aerodynamic environment of weather encounters.

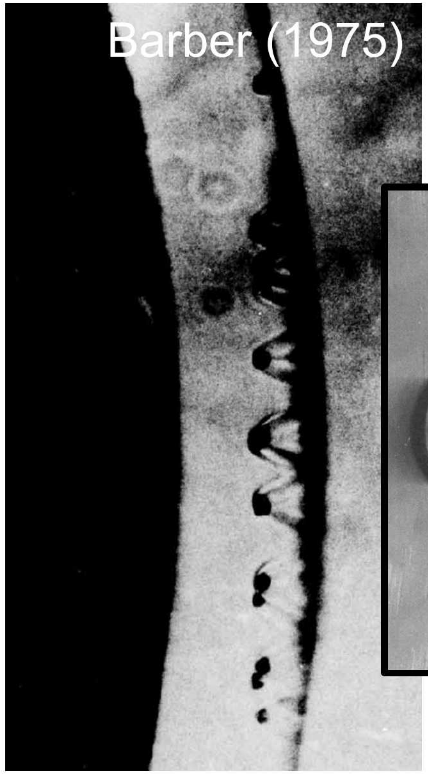
This is limited in shock tubes, gas guns, even sled tracks.

Primary concern: Particles create unsteady shock motion…



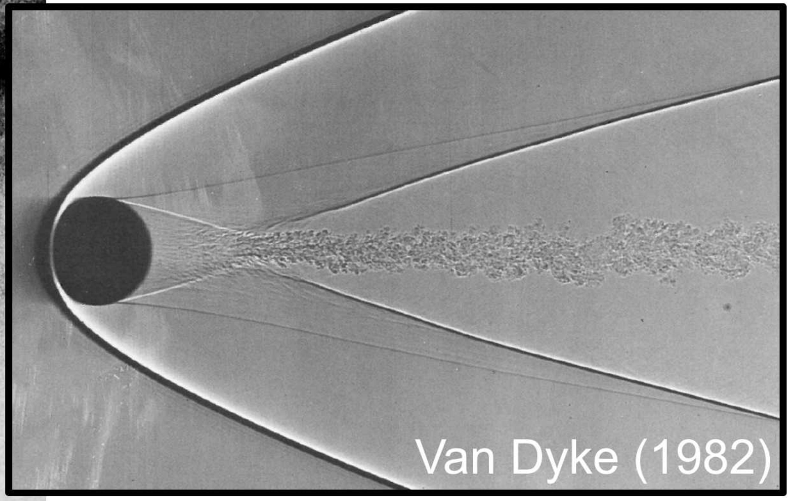
Holden (1976)





Barber (1975)

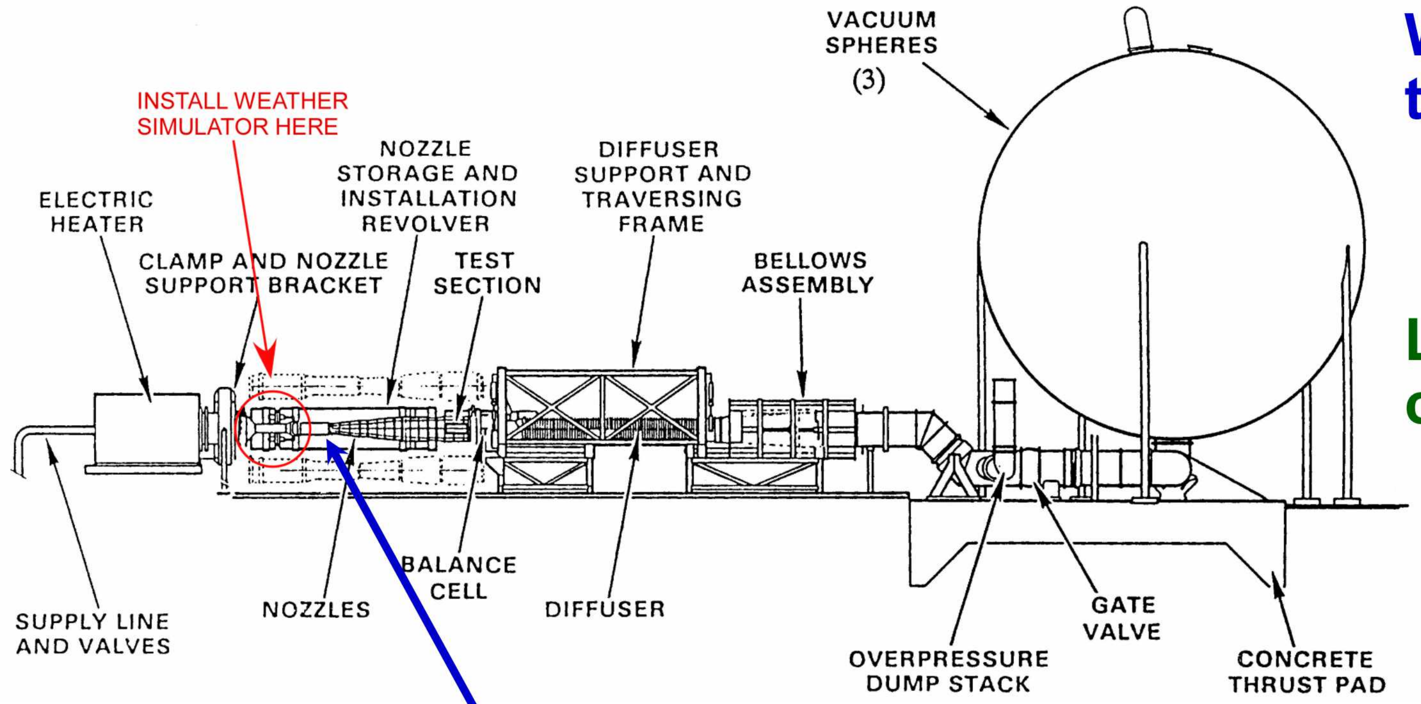
…augmented by the particle wake…



Van Dyke (1982)

…which cause pressure and temperature spikes.

Modifying HWT for weather testing

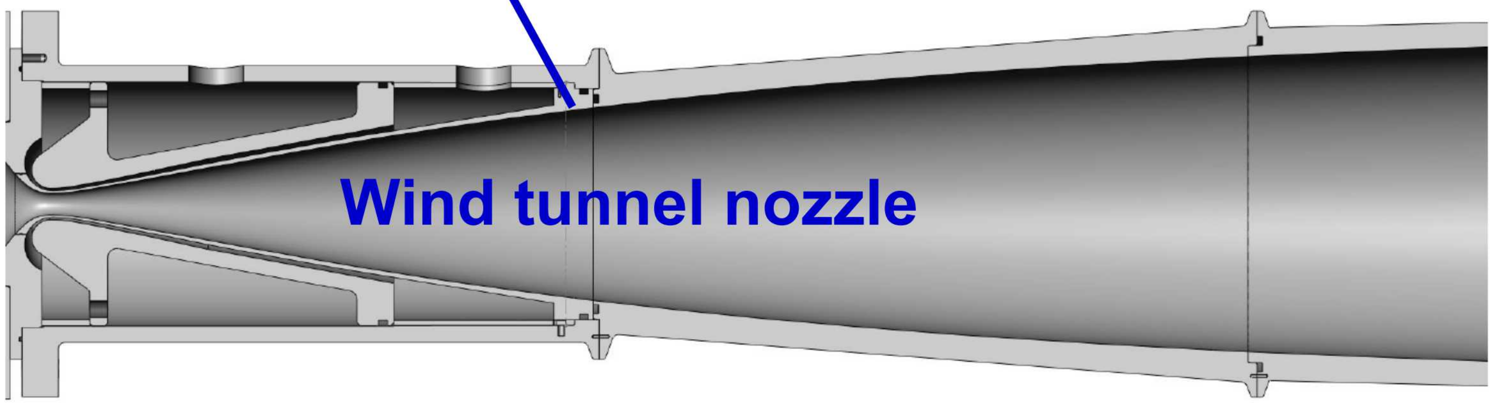


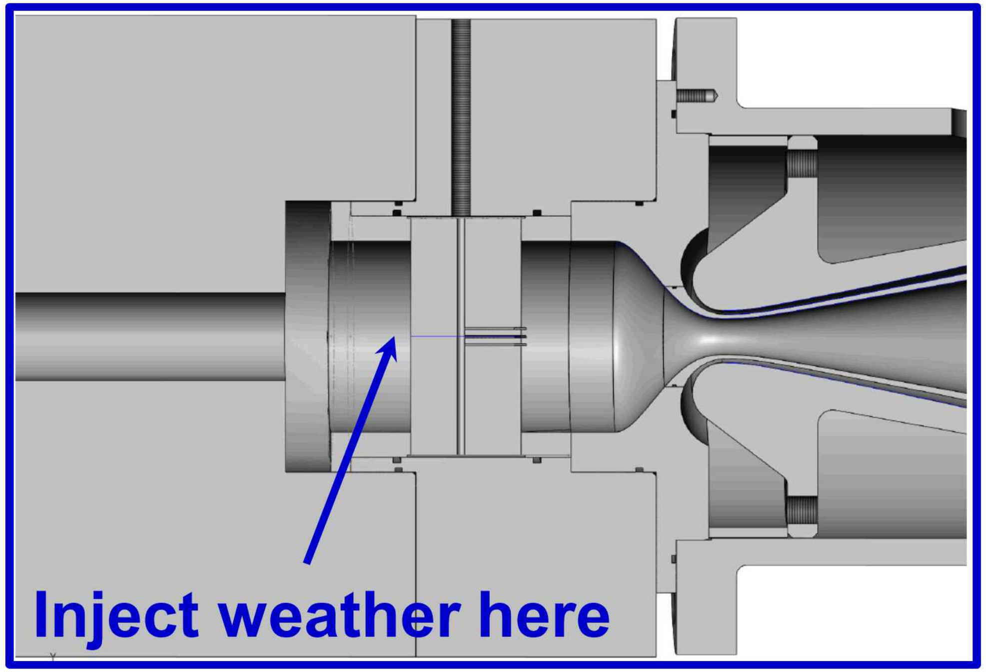
We are engineering tunnel modifications to incorporate weather injection.

Solid particles first, liquid droplets eventually.

Laser diagnostics for particle and flow characteristics.

Fast MEMS sensors can measure surface response.

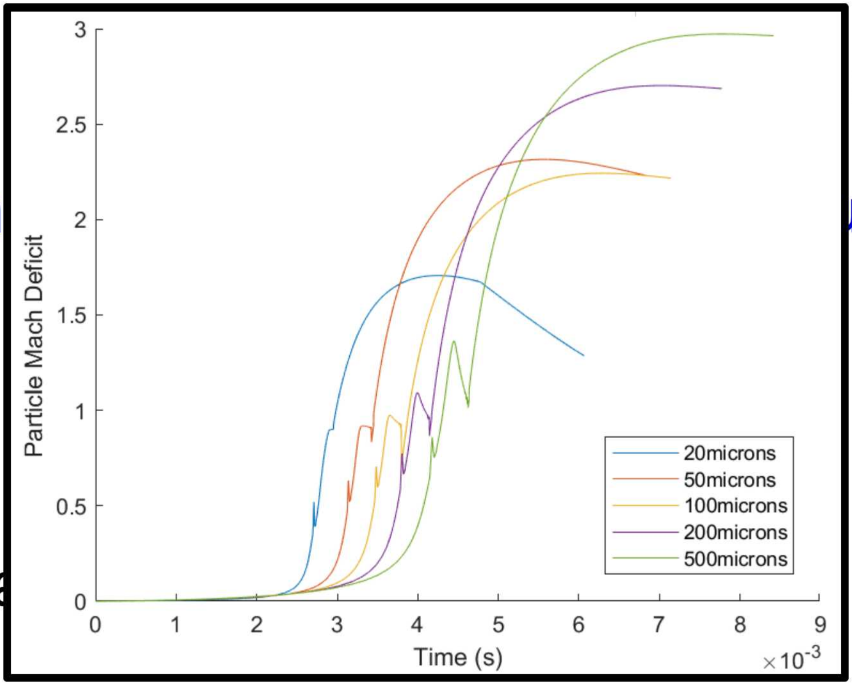




What are the problems with weather in s?

Analysis says it is not possible to seed a rain unnel.

- Acceleration through the nozzle will destroy it.



Anecdotal evidence says we have seen large

- But we don’t know how fast or if deformed.
- Analysis is based on laws that may not well ma

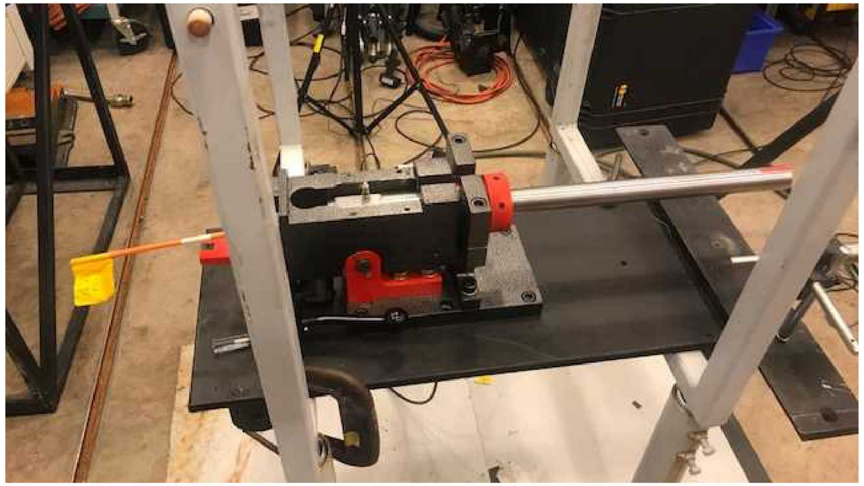
Analysis also says particulates will not accelerate to match flow velocity.

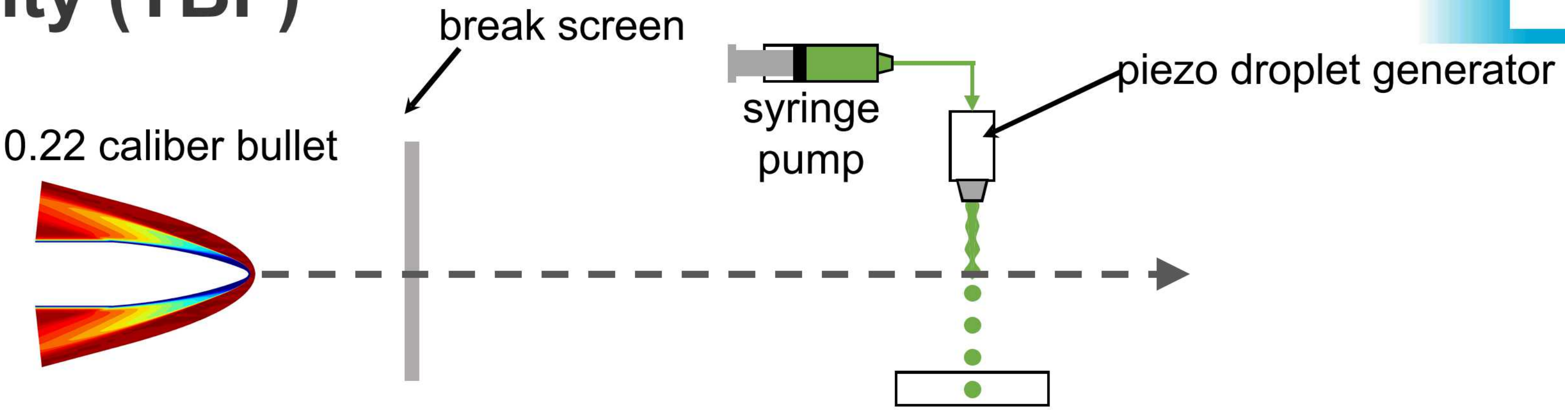
- This hasn’t stopped previous testing programs.
- Smaller particles have too low a Reynolds number to be relevant.

No single hypersonic test facility can fully replicate the hypersonic environment.

Corollary: No single weather test facility can fully replicate the weather environment.

Terminal Ballistics Facility (TBF)



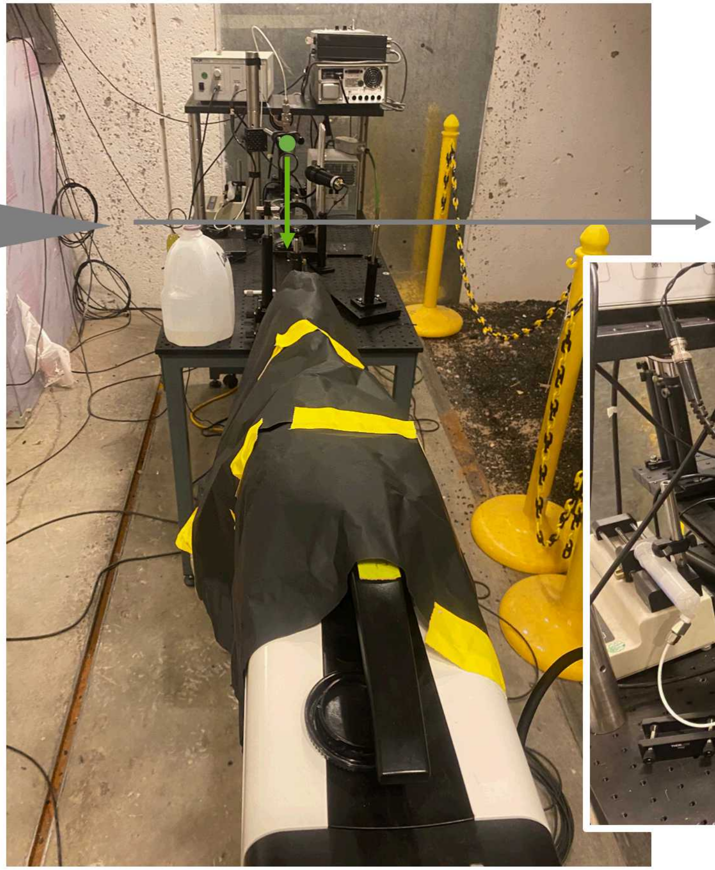


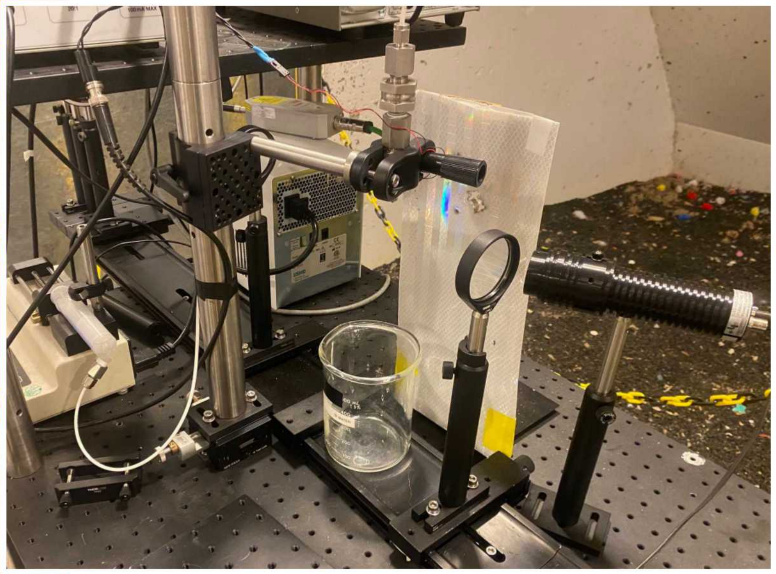
Essentially an indoor gun range where we can fire a bullet past a droplet up to Mach 4.75.

Gives us a different means of generating shock/droplet interactions that the wind tunnel or a shock tube.

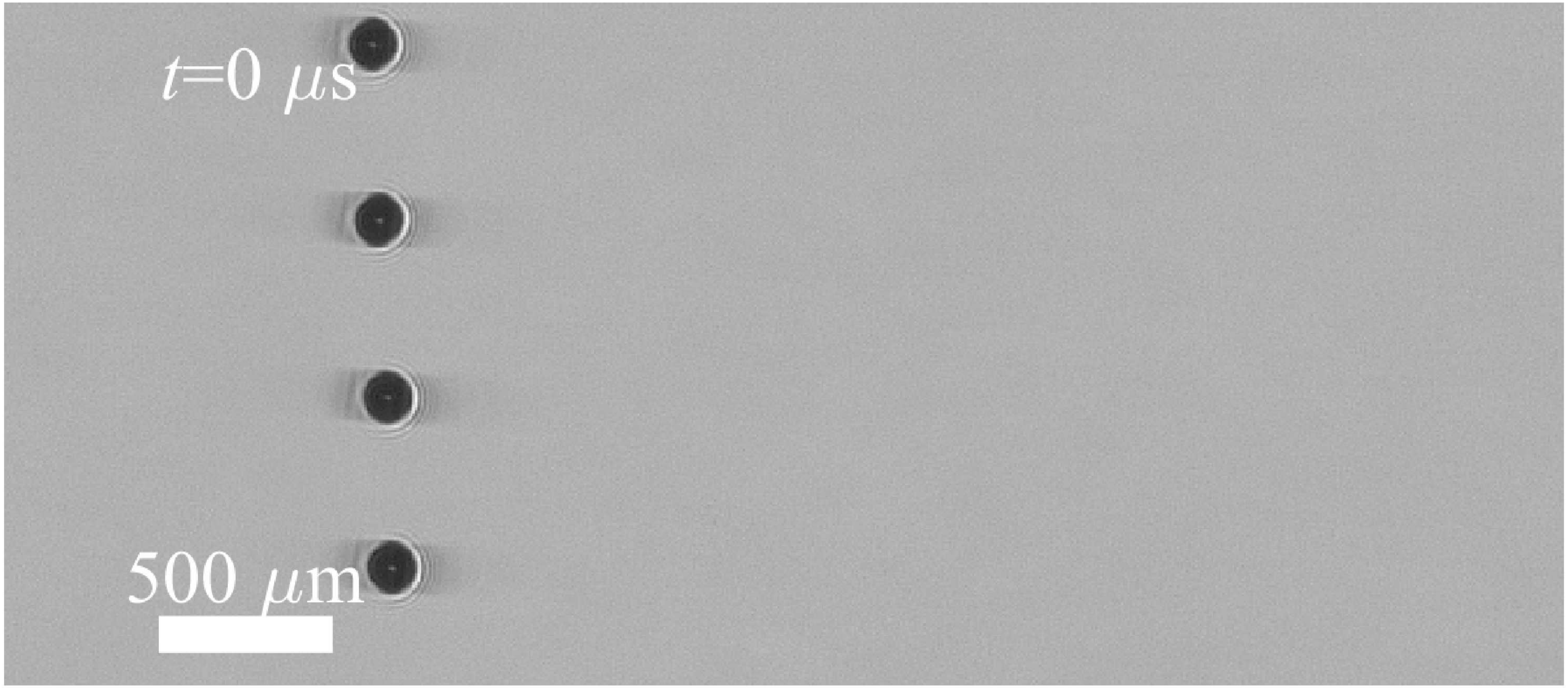
The conical shock from a bullet more closely resembles the shock for an RV.

Very different from the current model.





Shot 79 (bullet traveling 4055 ft/s = 1.236 km/s)



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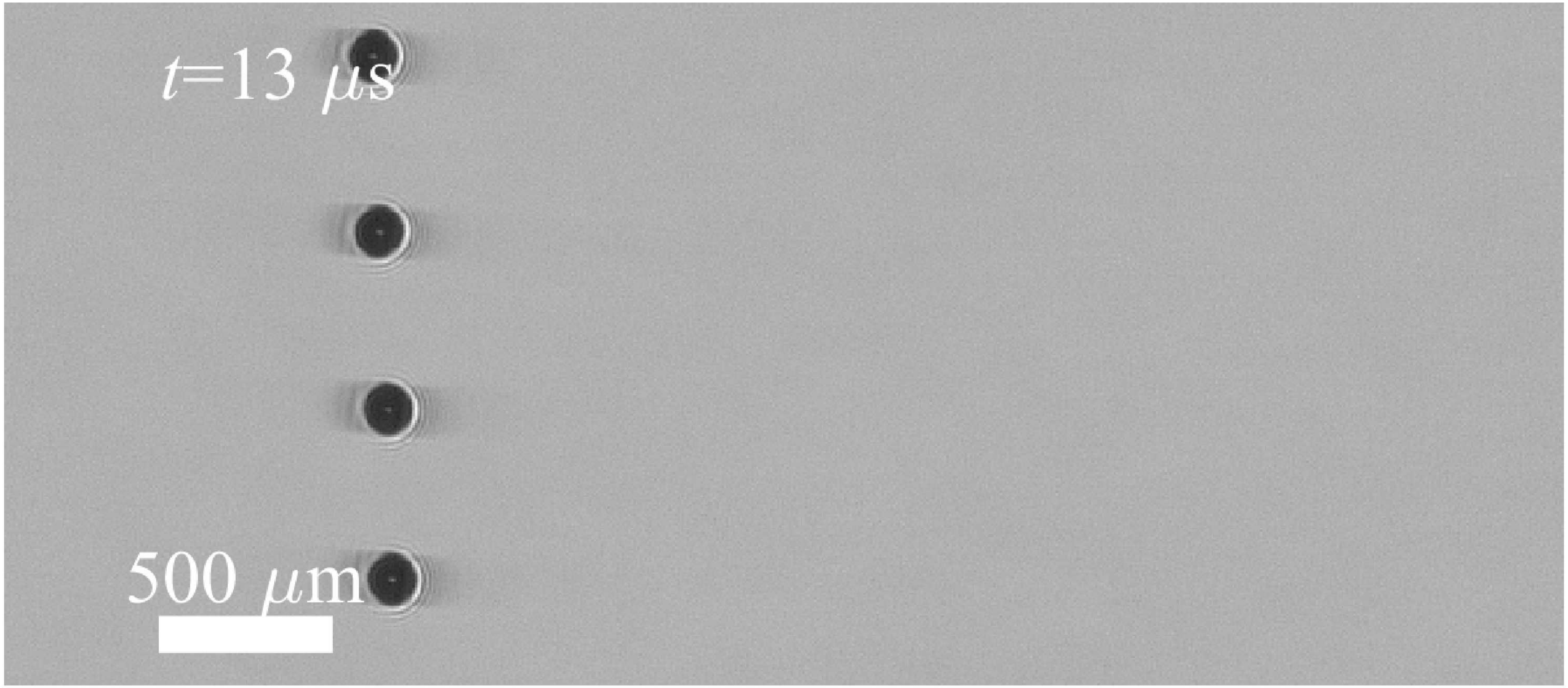

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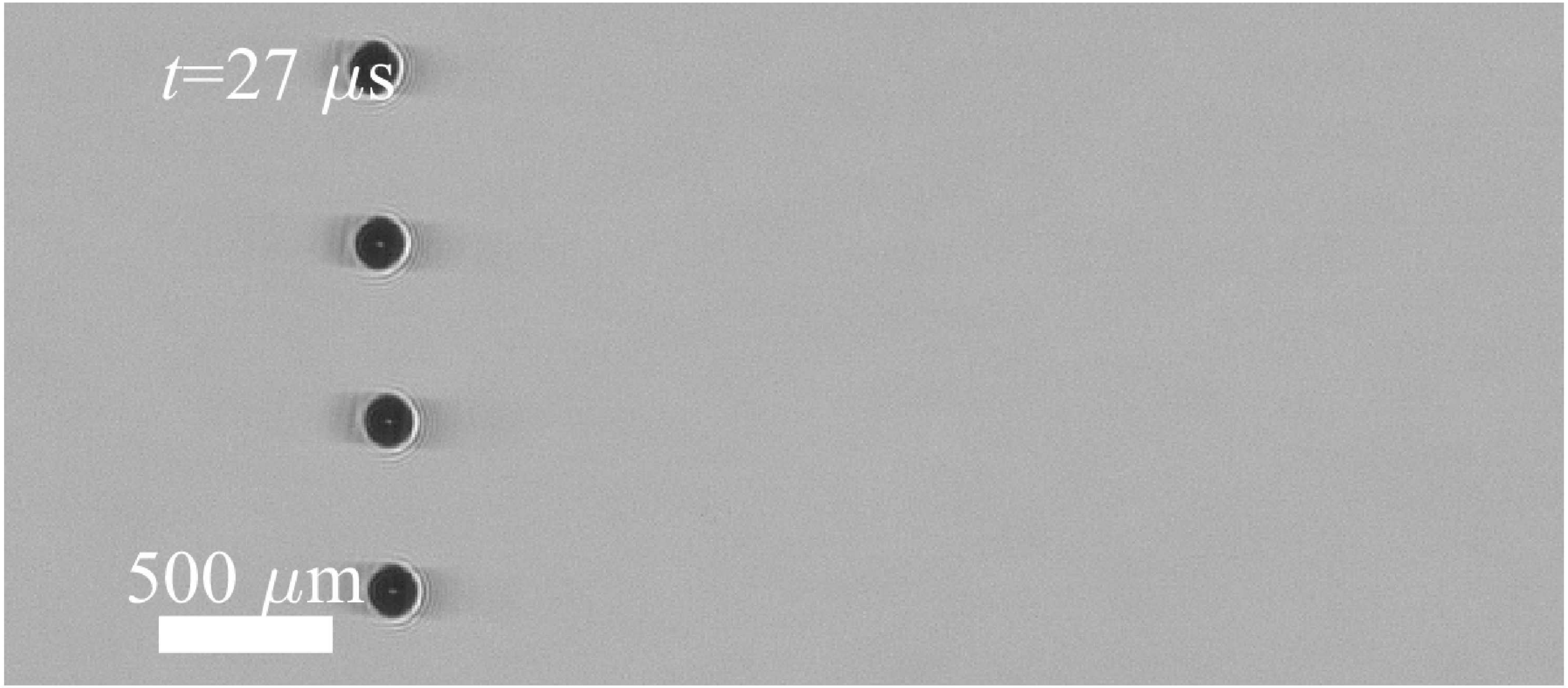

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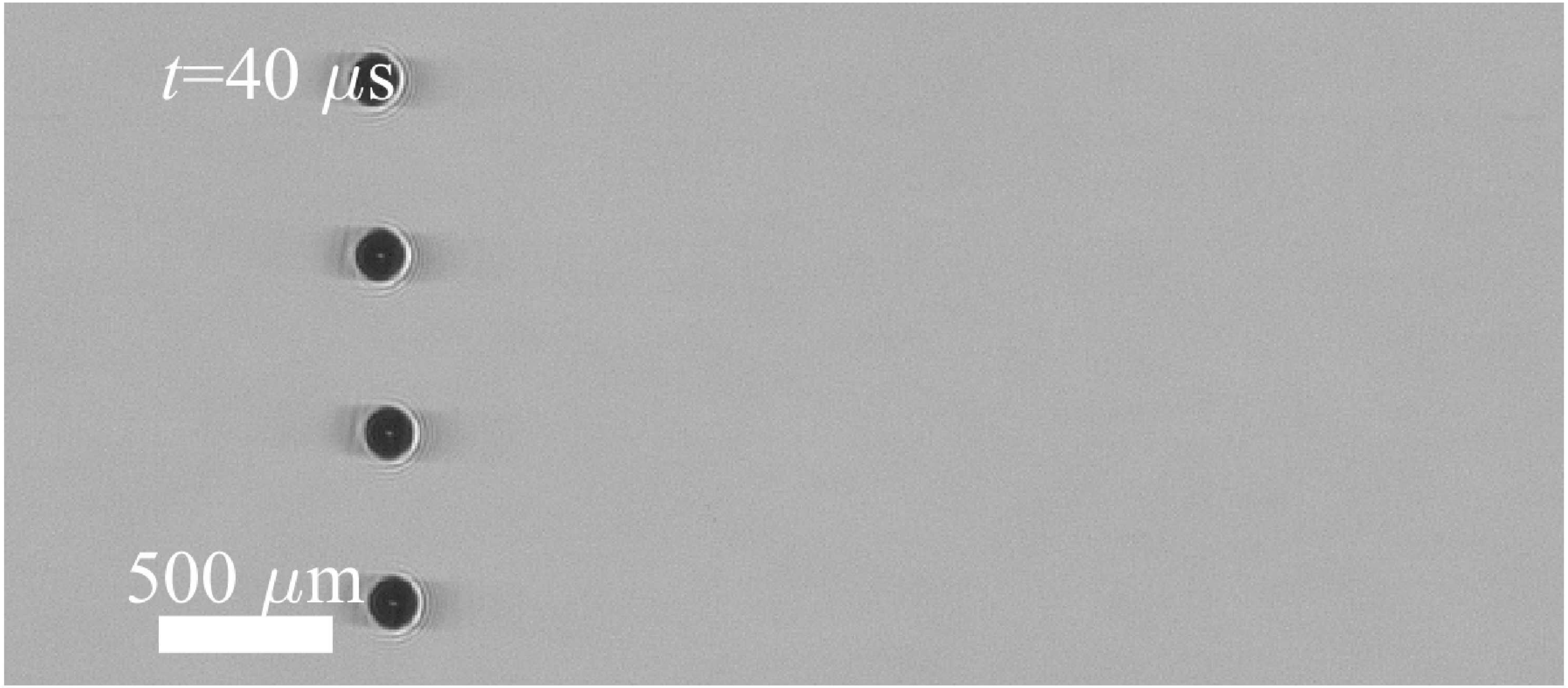

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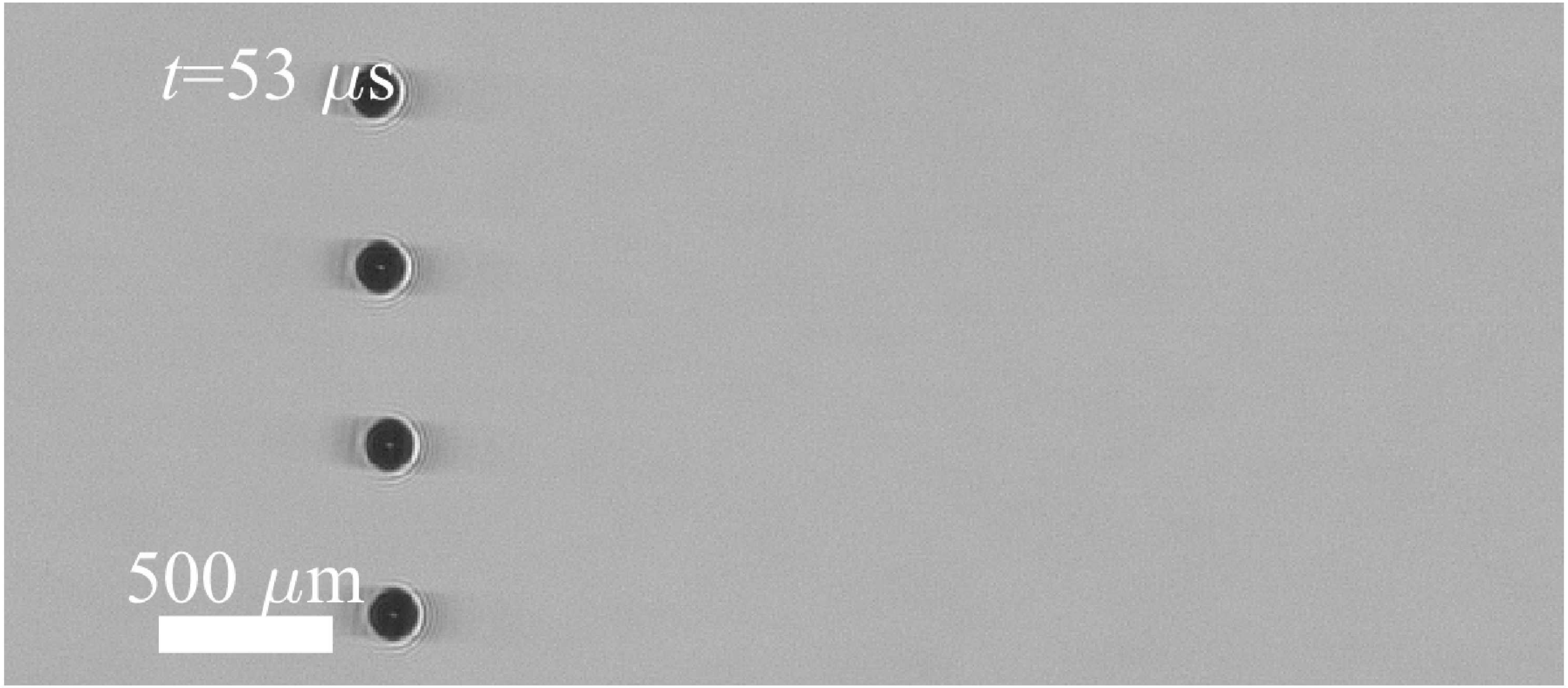

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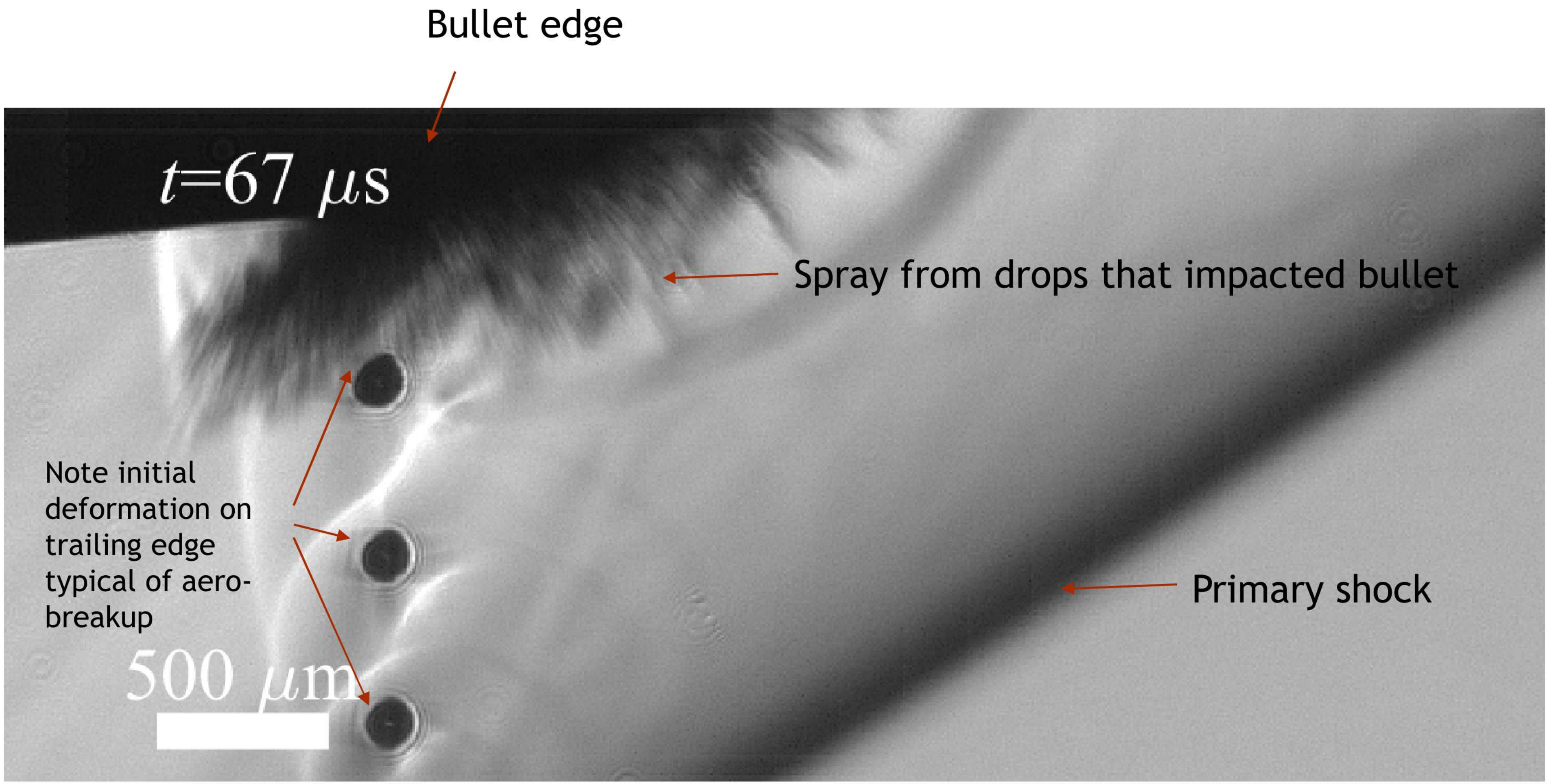

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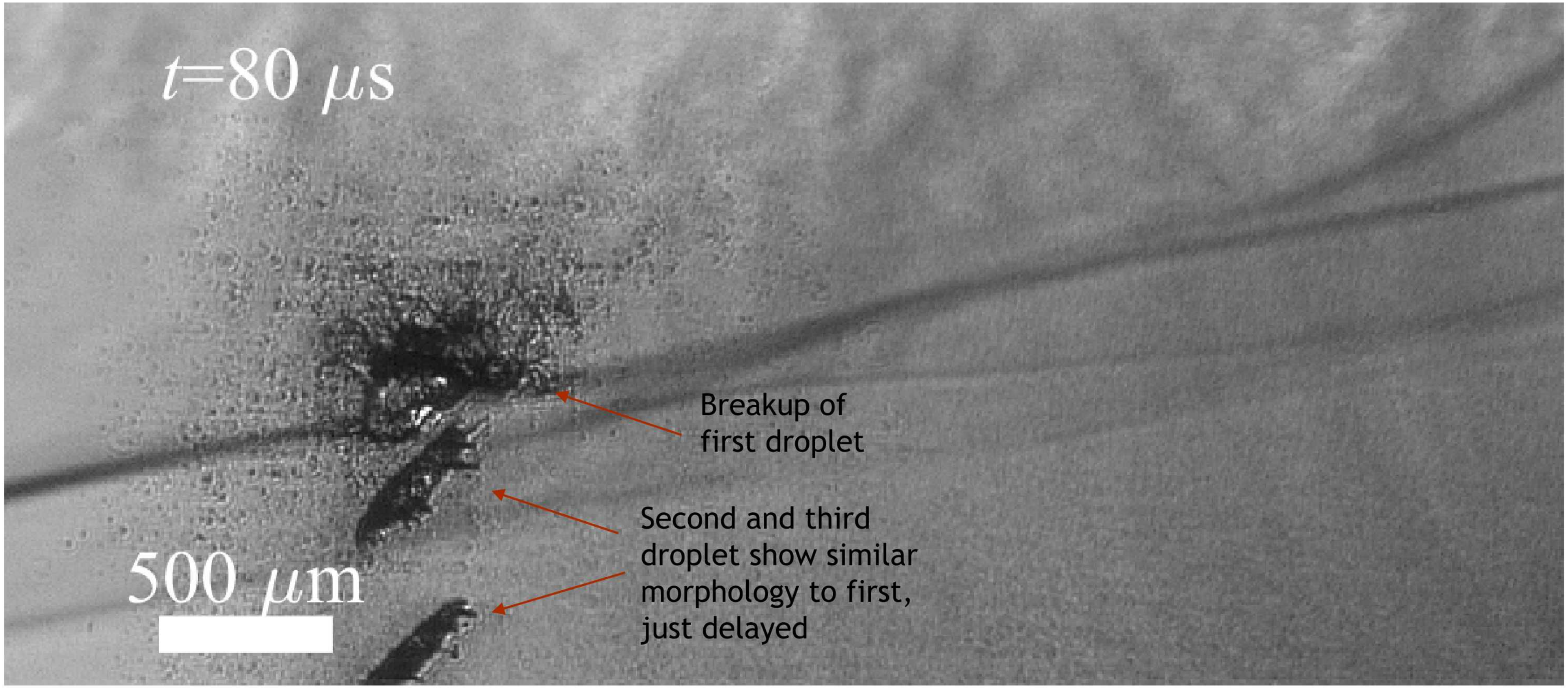

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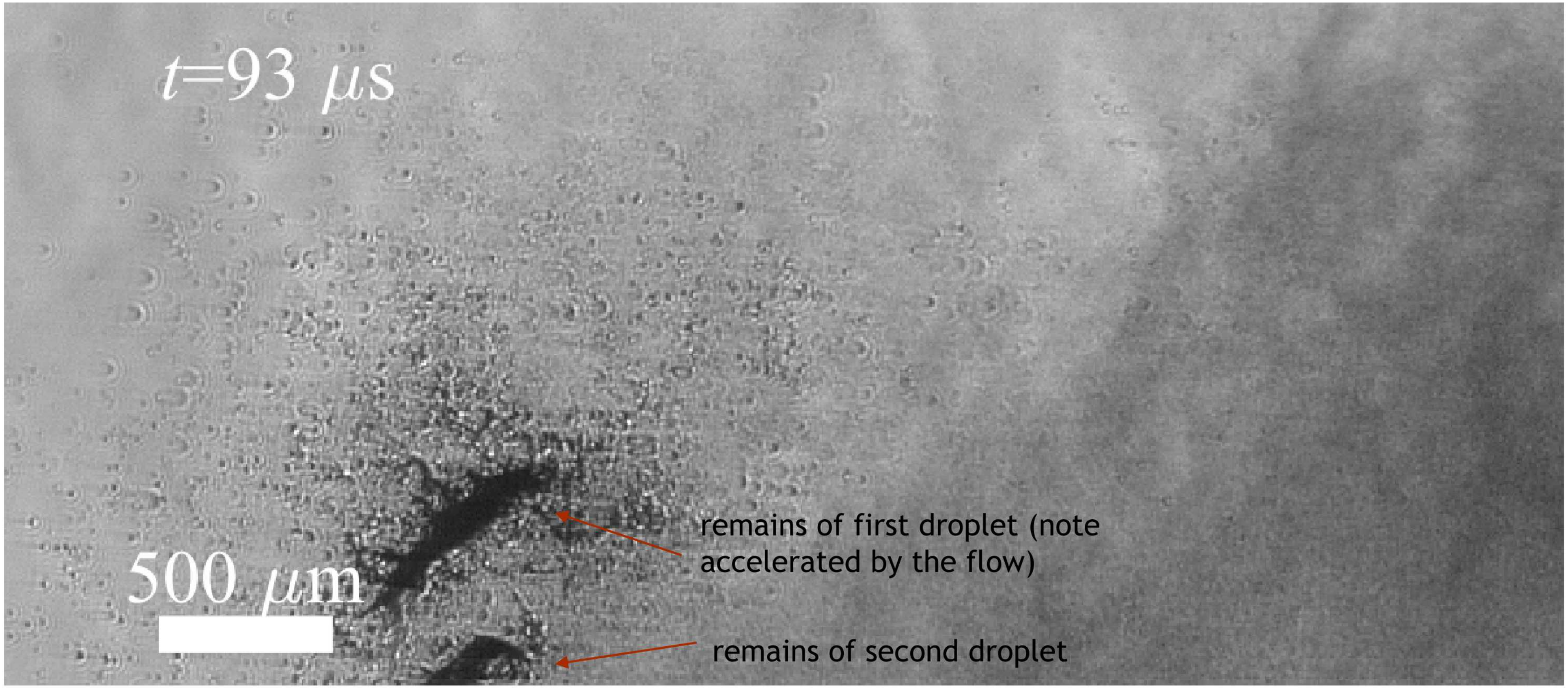

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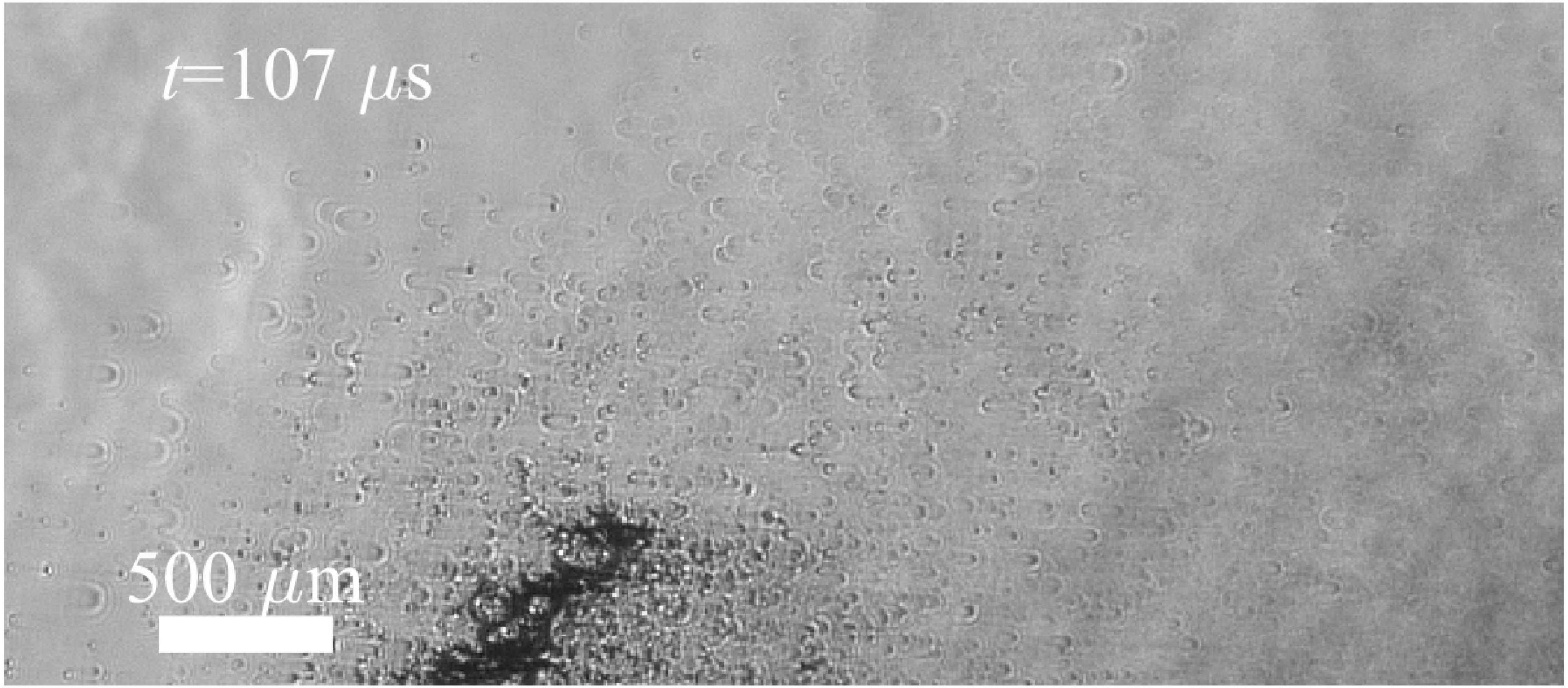

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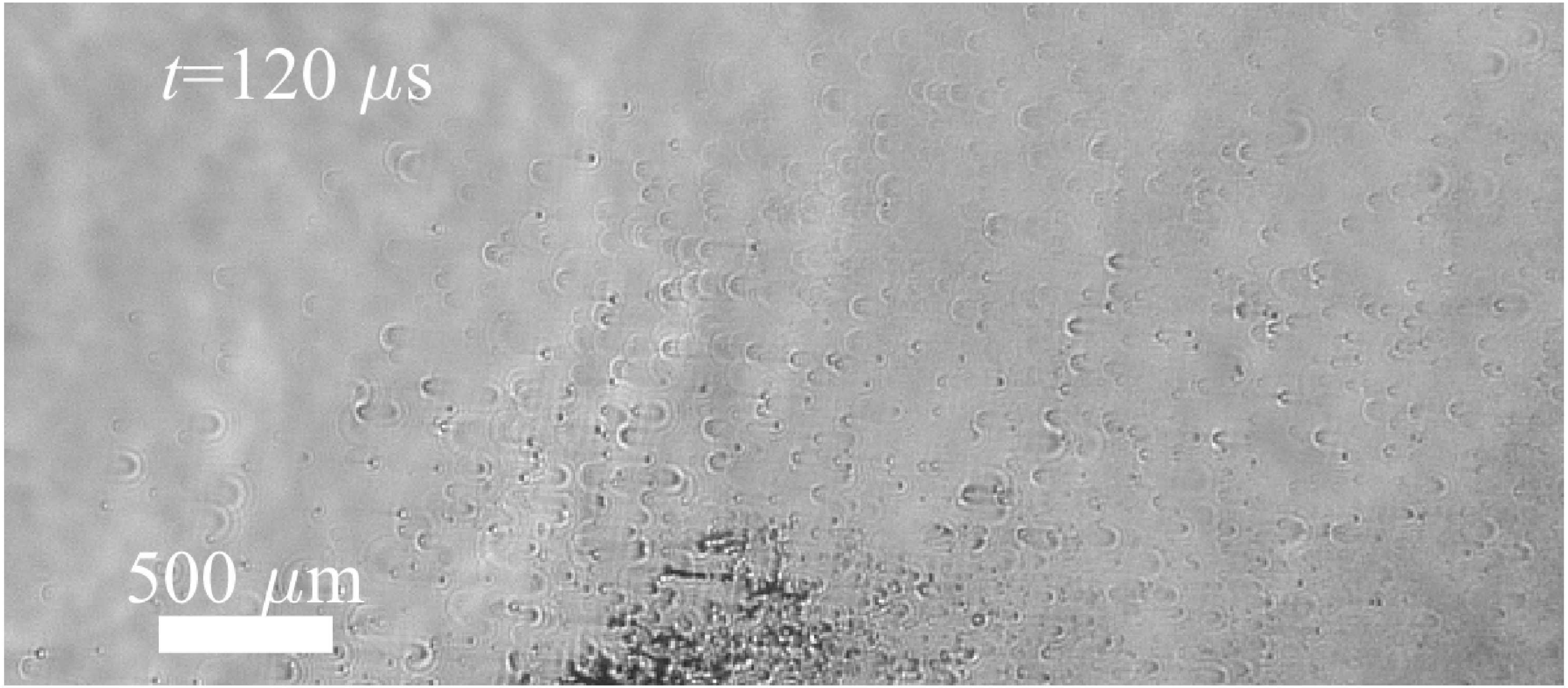

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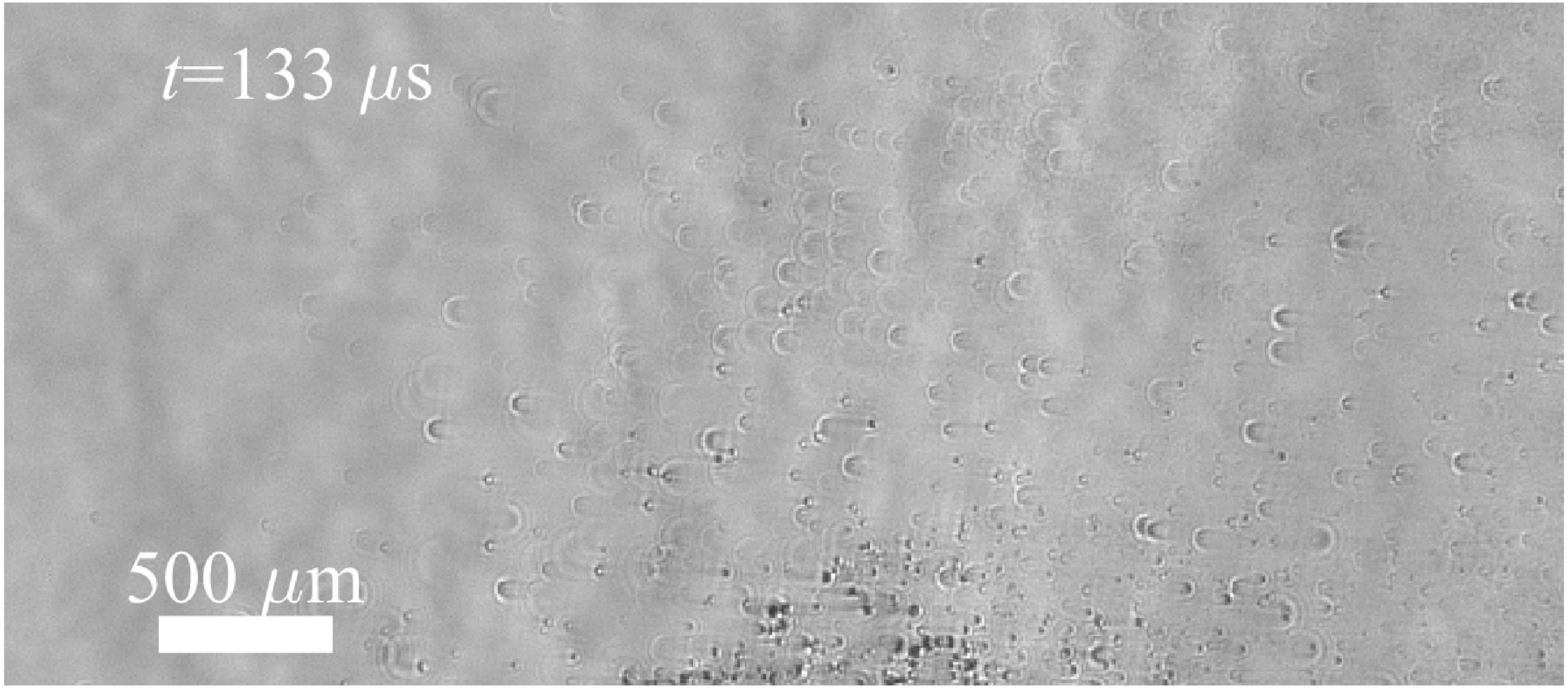
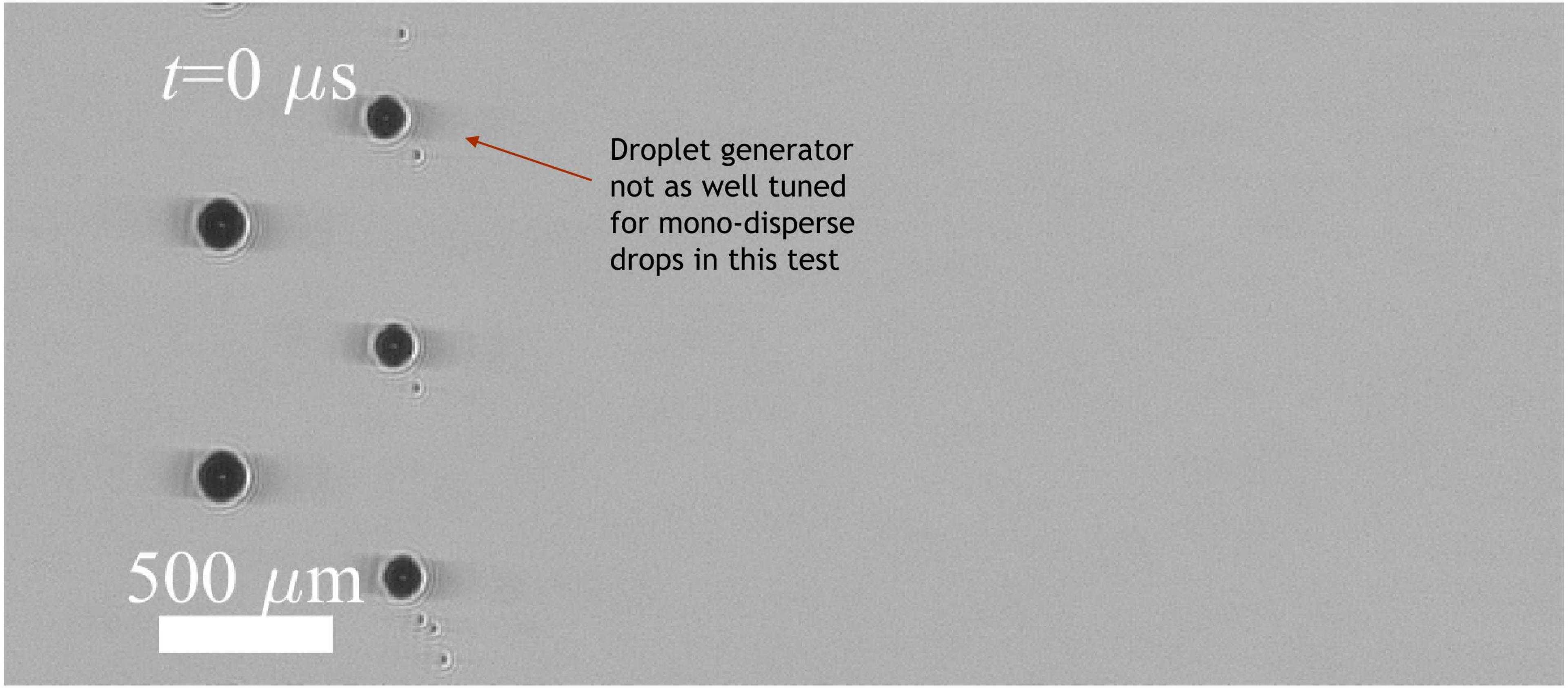
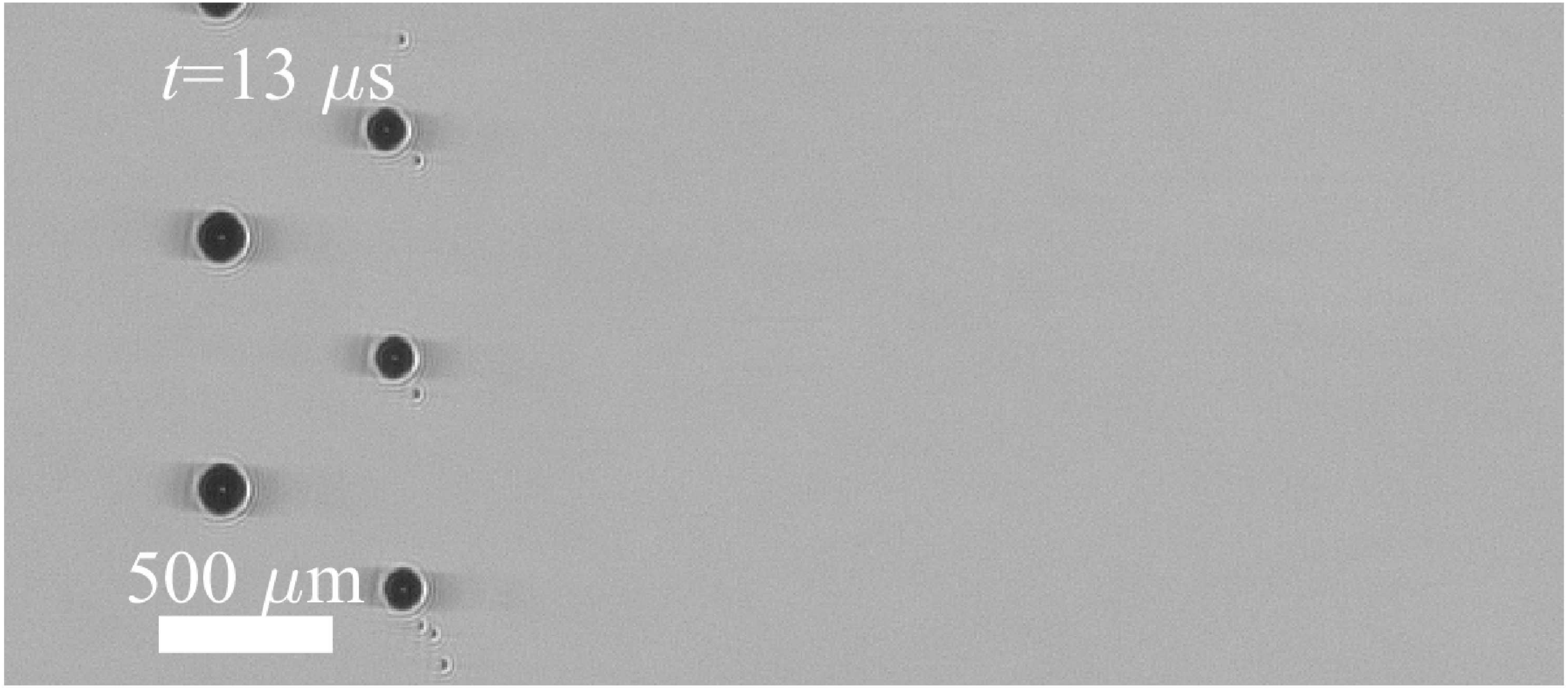


Shot 81 (bullet traveling 4158 ft/s = 1.267 km/s)



Droplet generator not as well tuned for mono-disperse drops in this test

Shot 81 (bullet traveling 4158 ft/s = 1.267 km/s)



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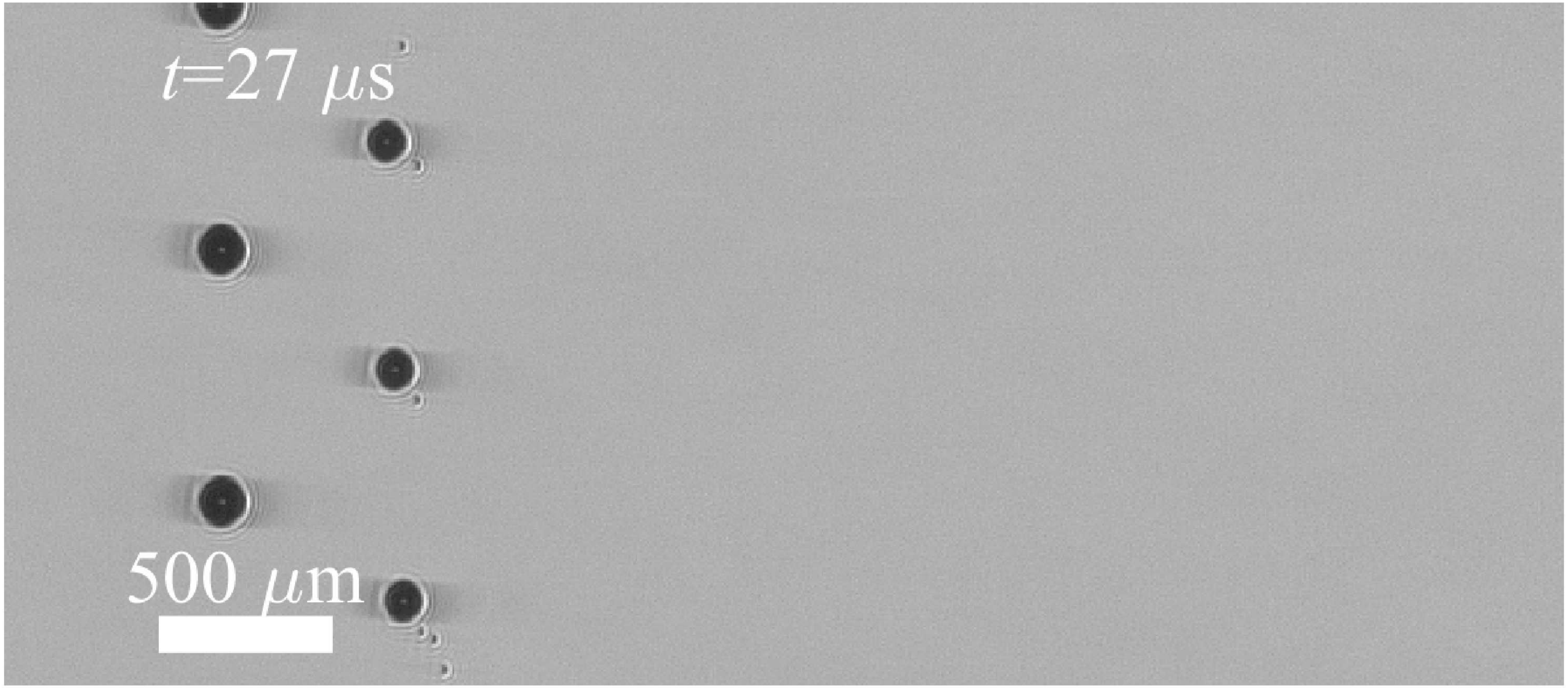

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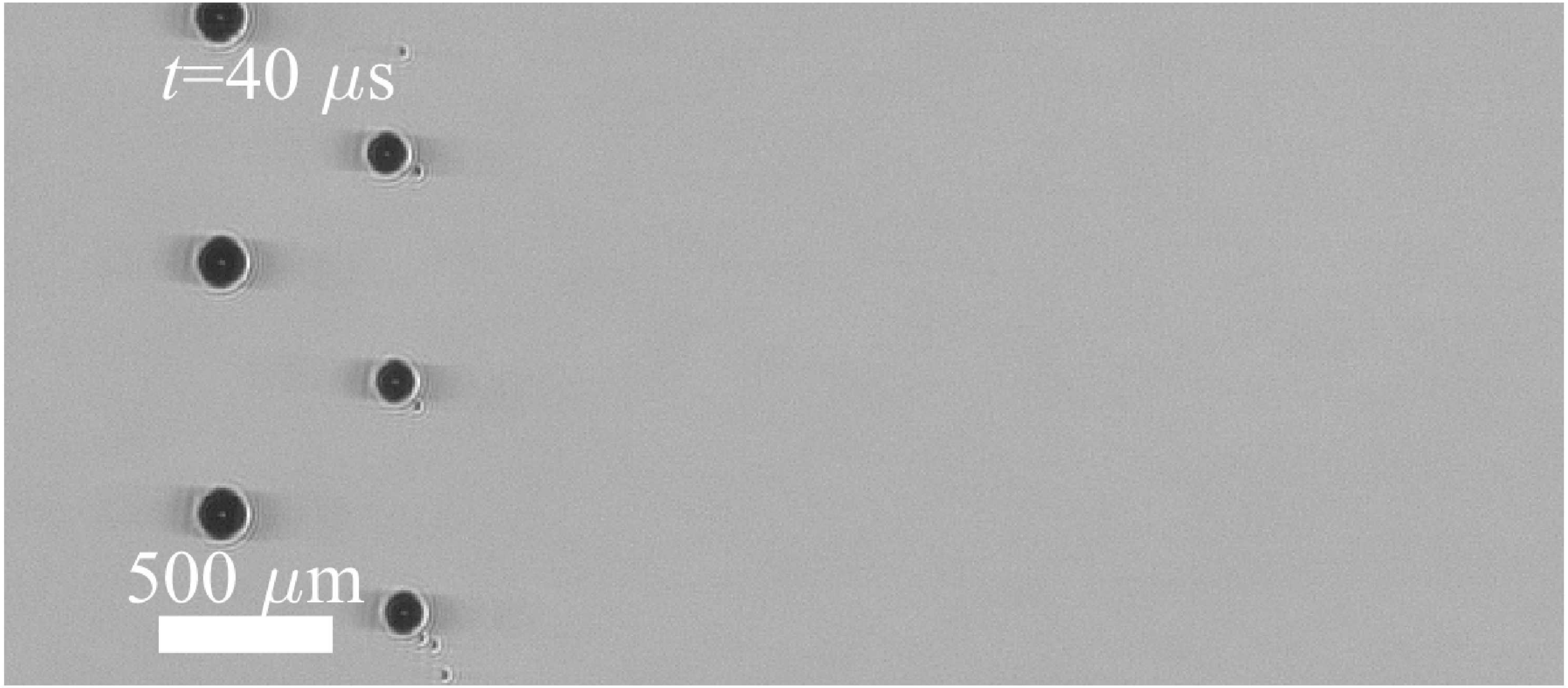

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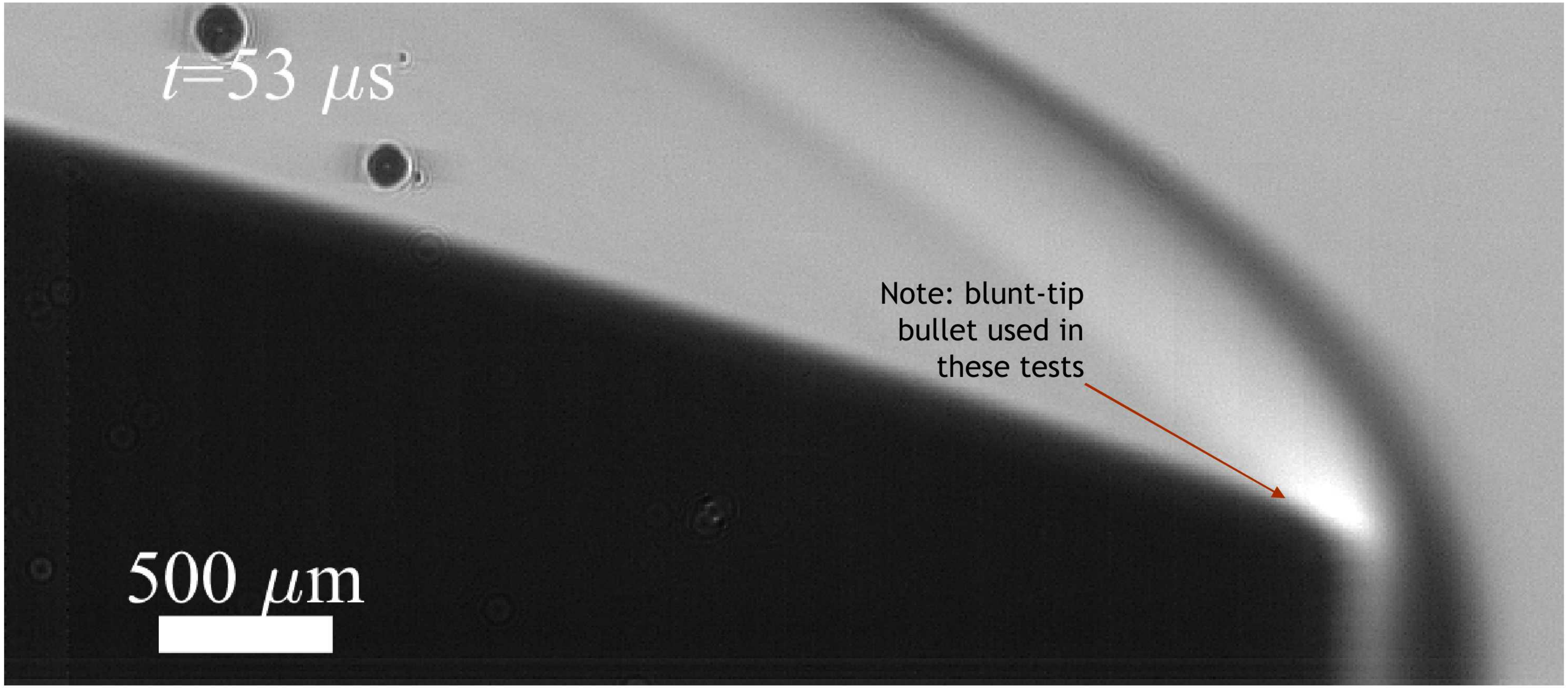
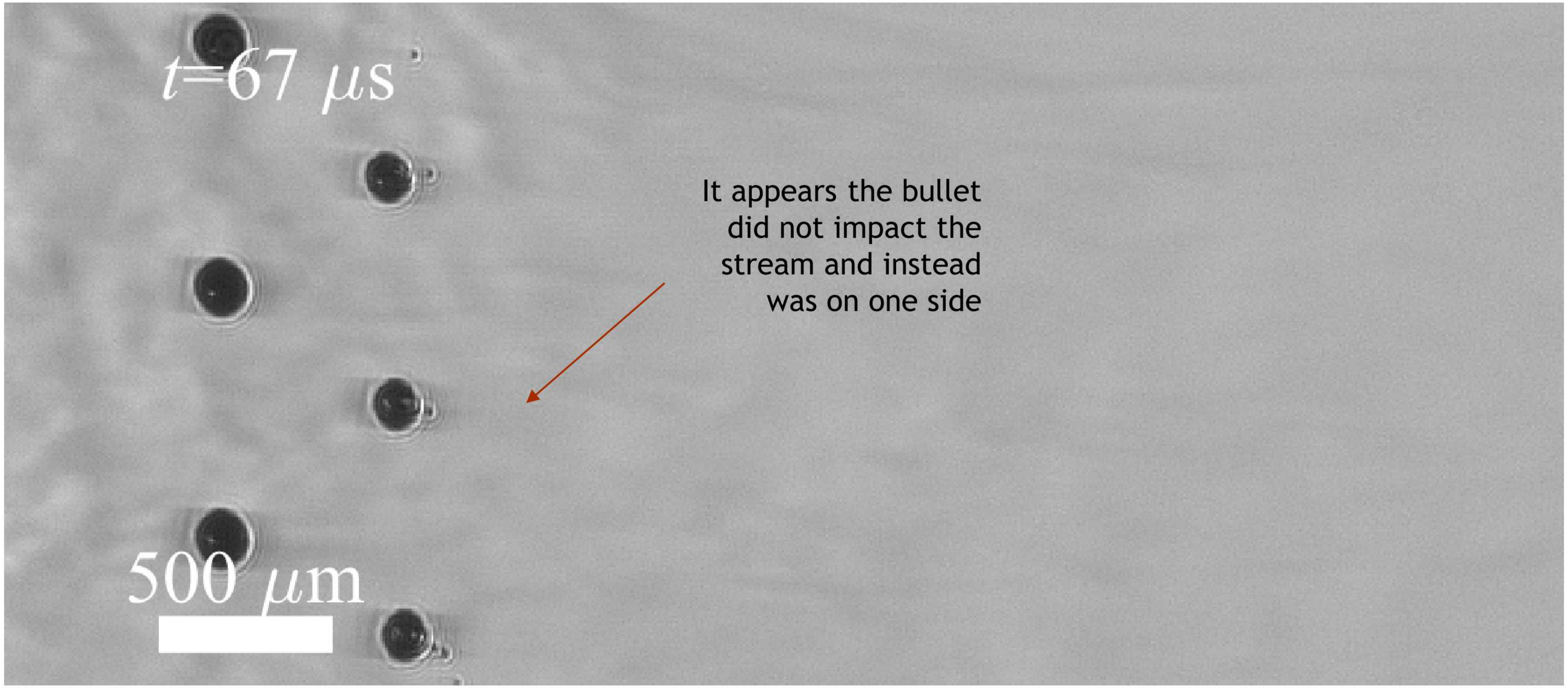


Note: blunt-tip bullet used in these tests

Shot 81 (bullet traveling 4158 ft/s = 1.267 km/s)



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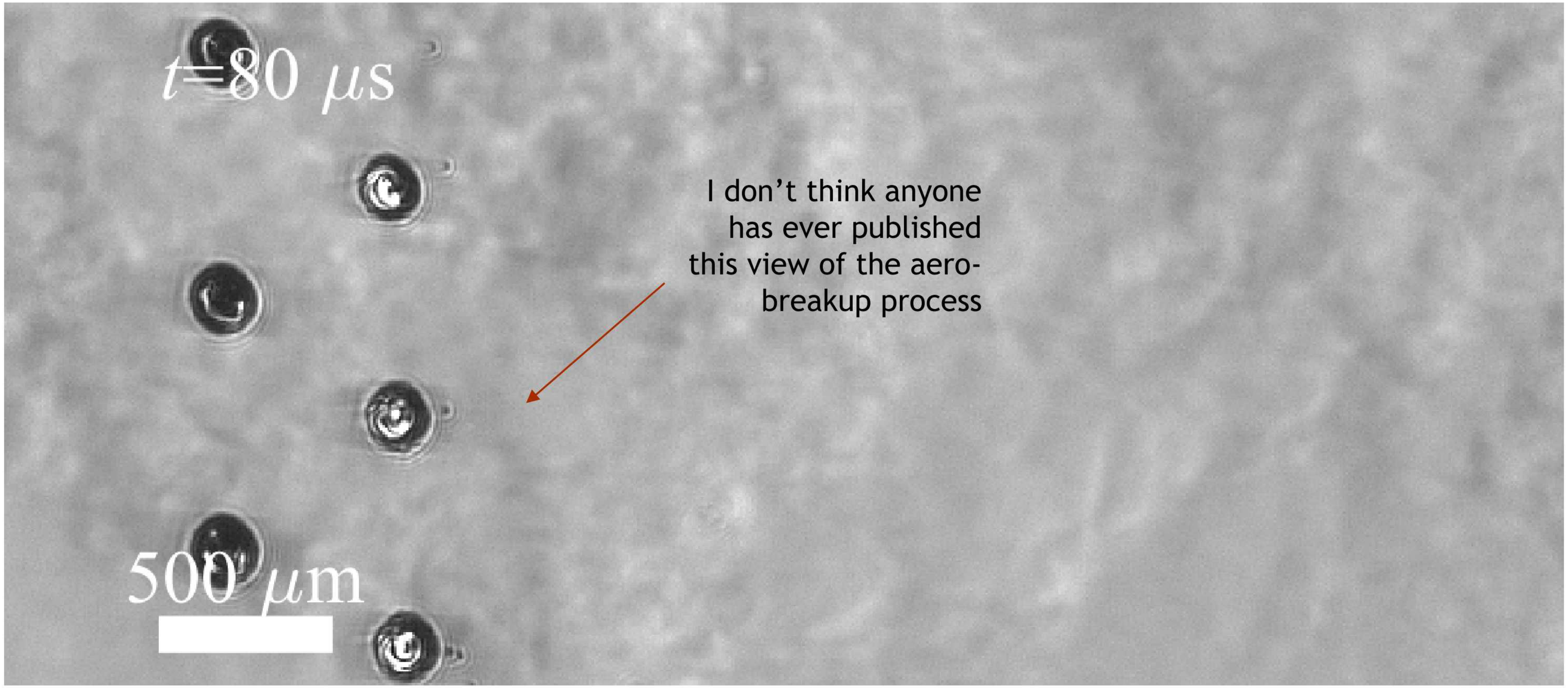

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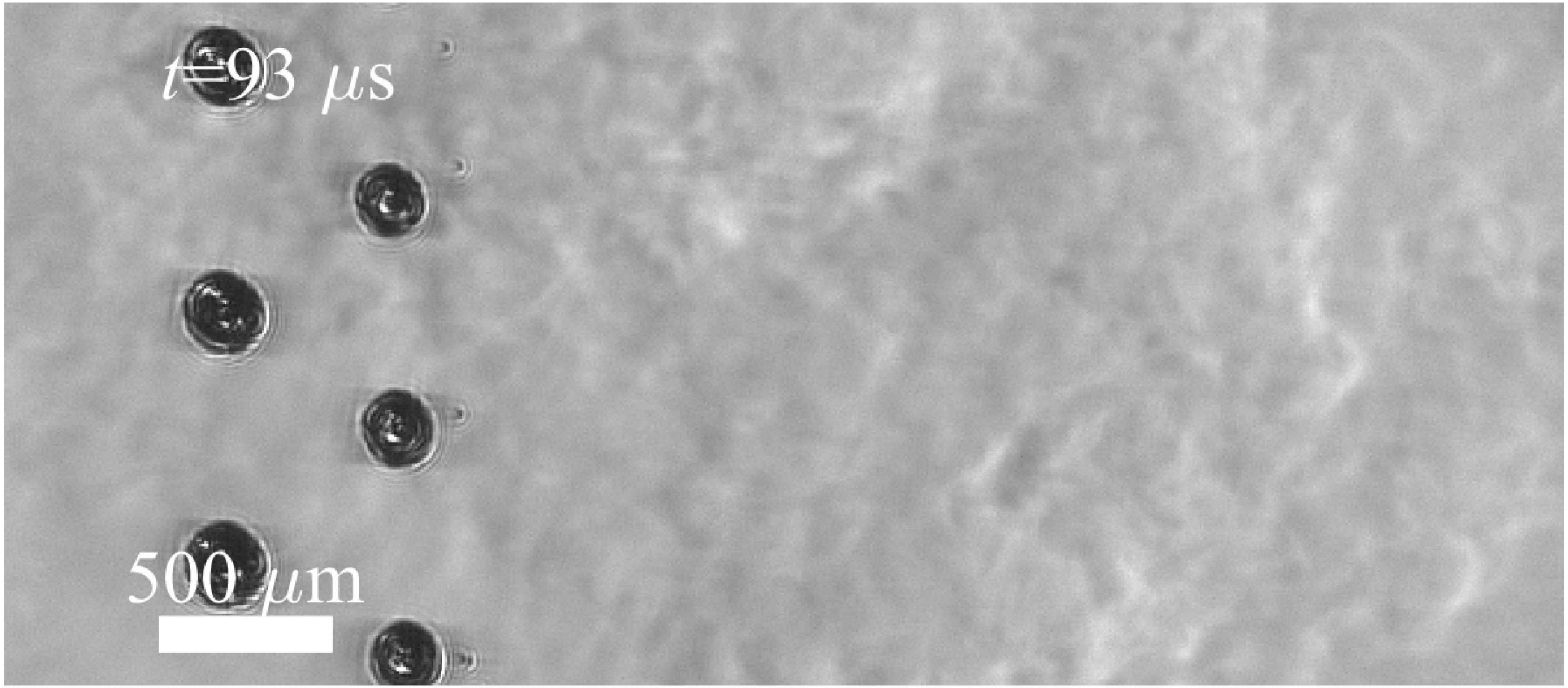

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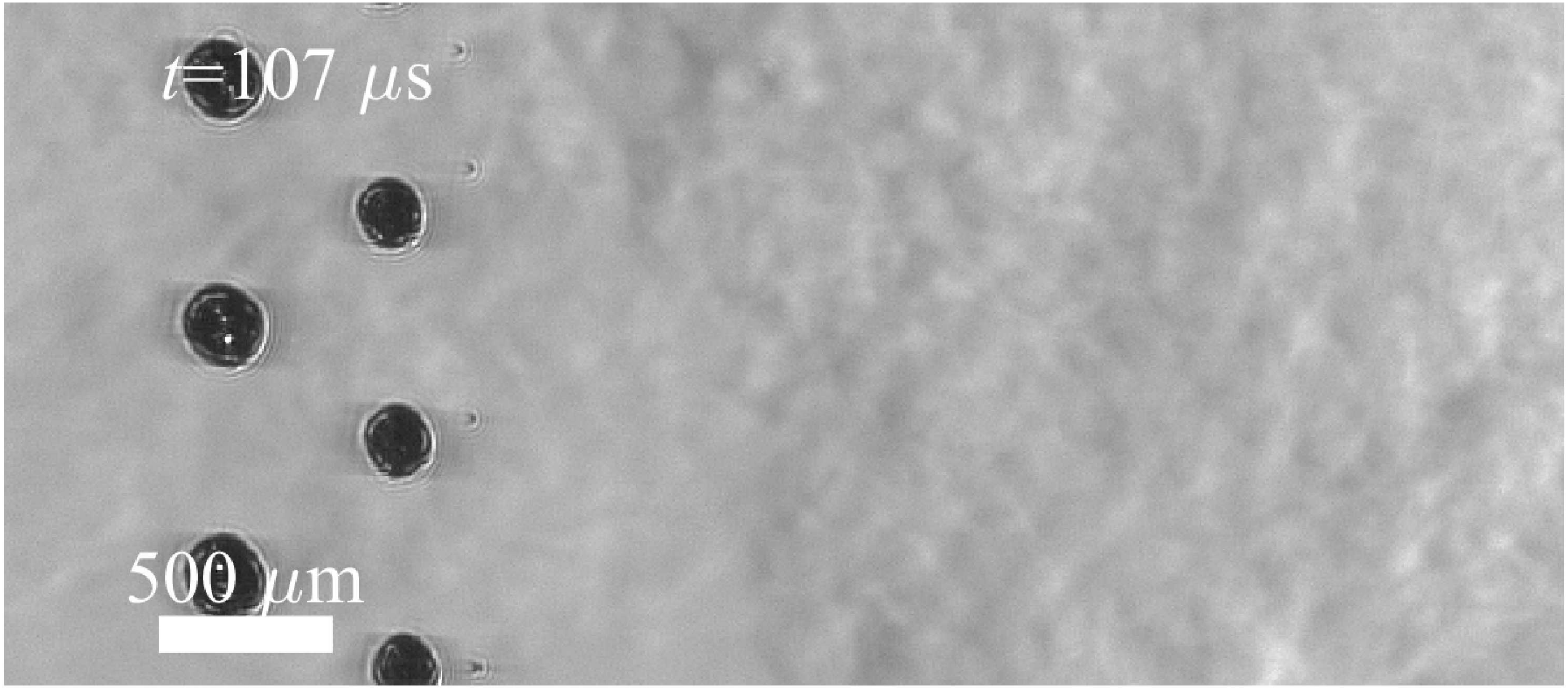

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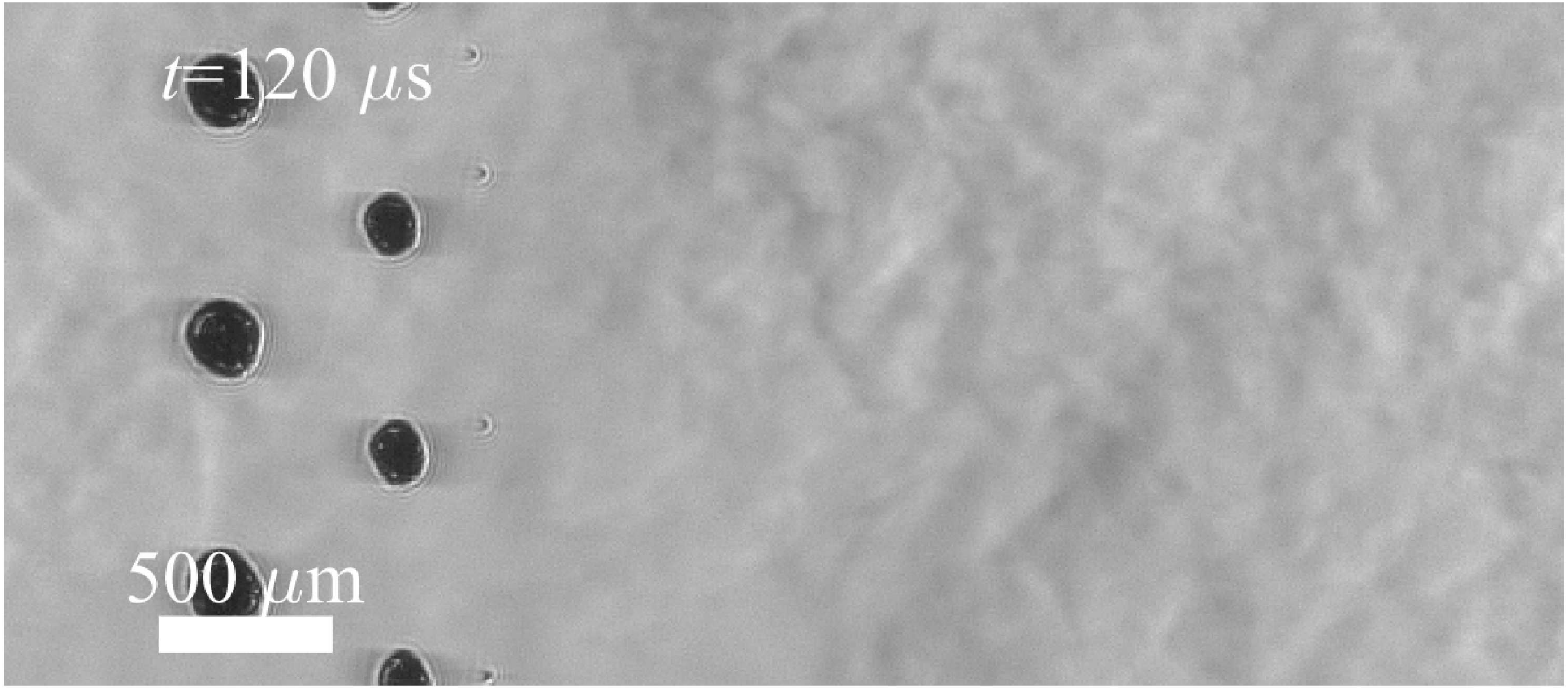

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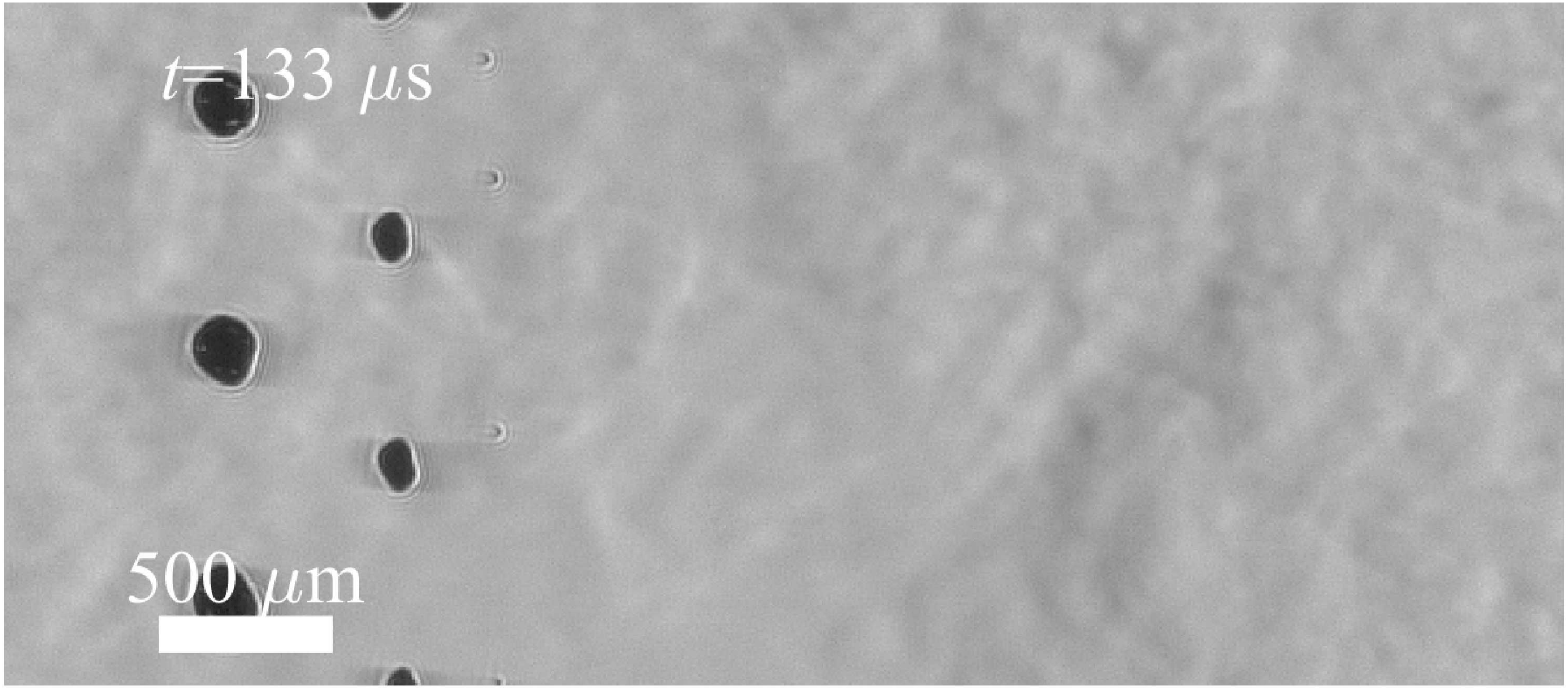

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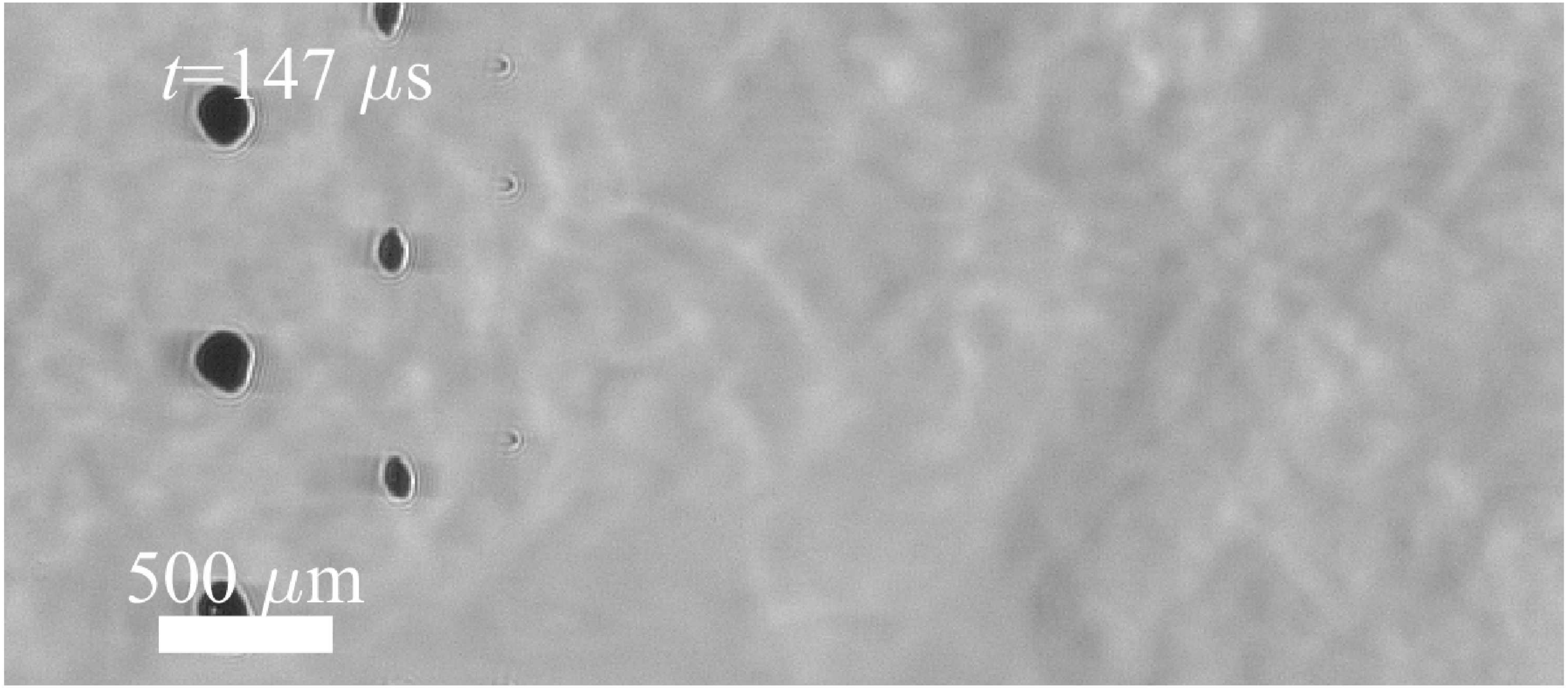

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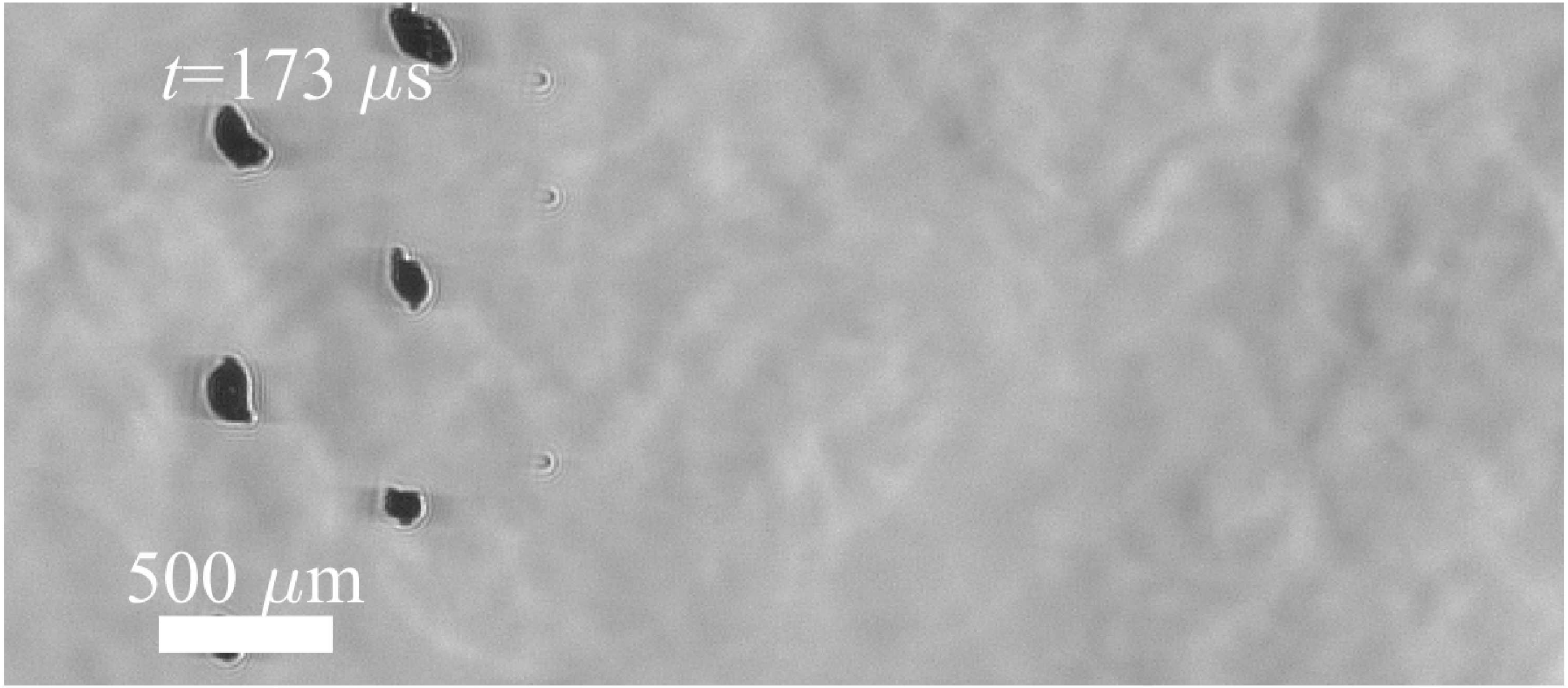

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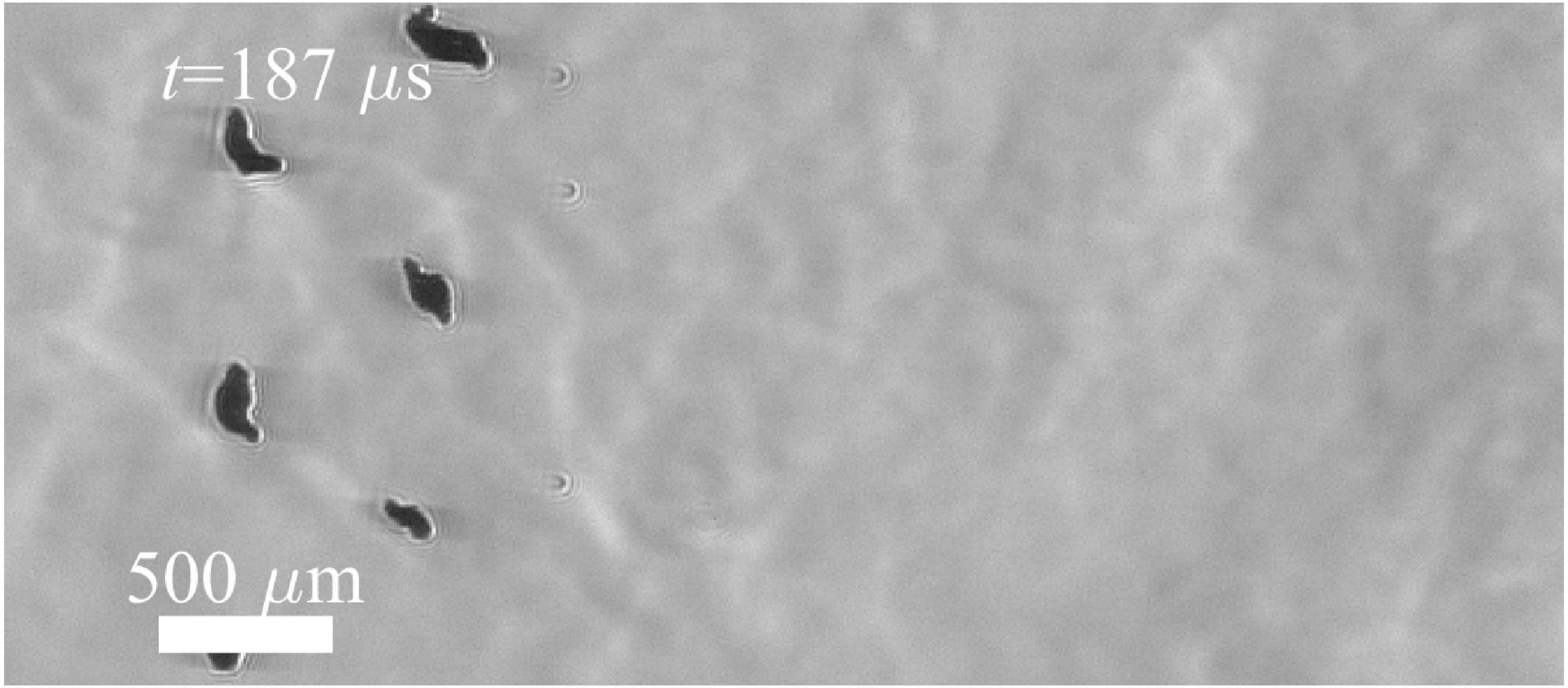

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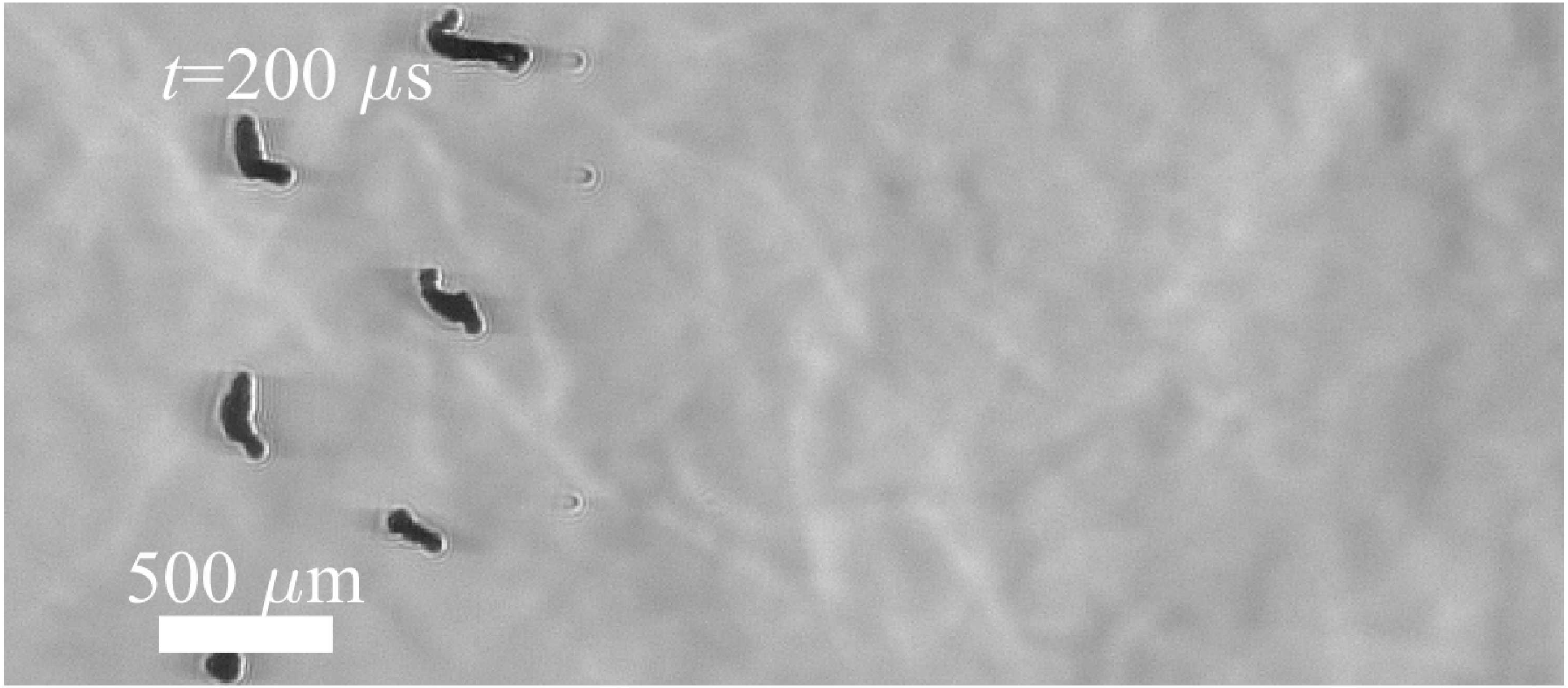

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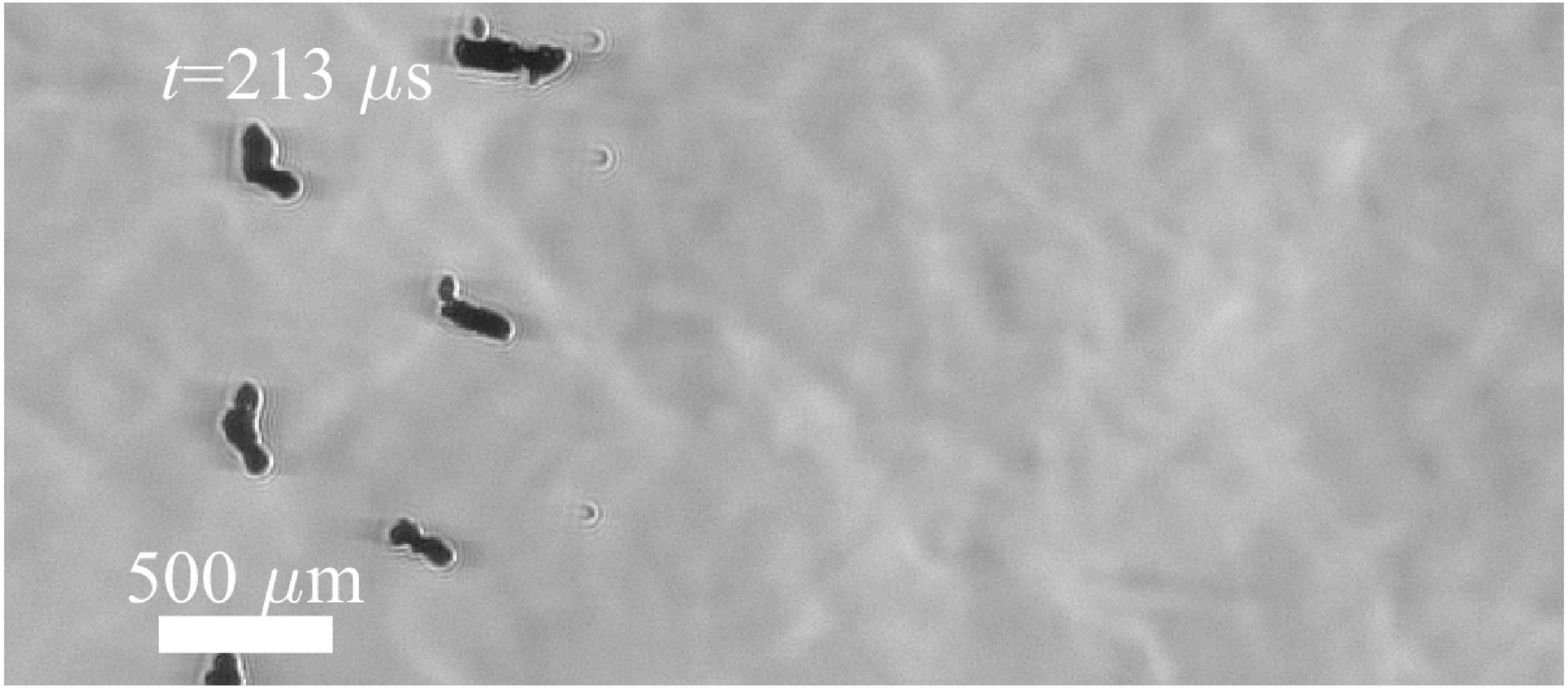

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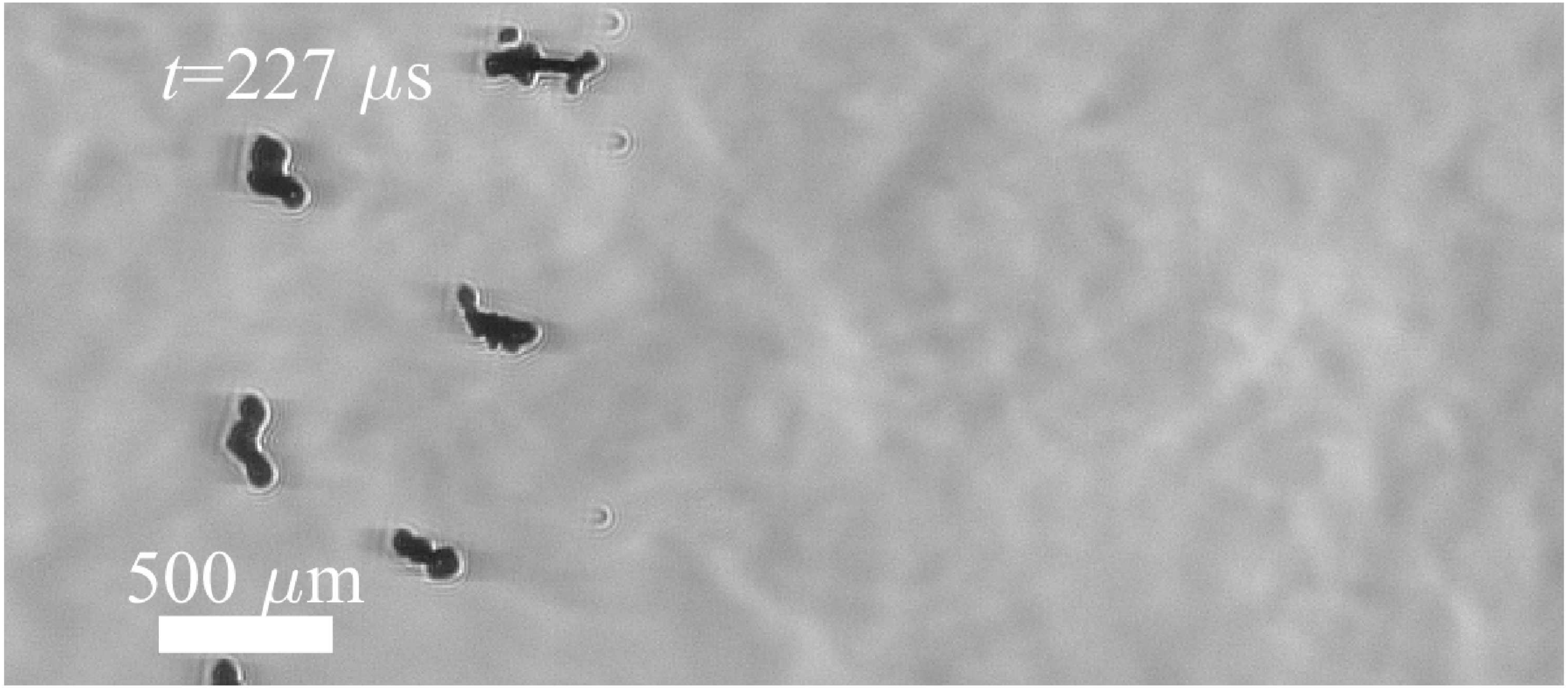

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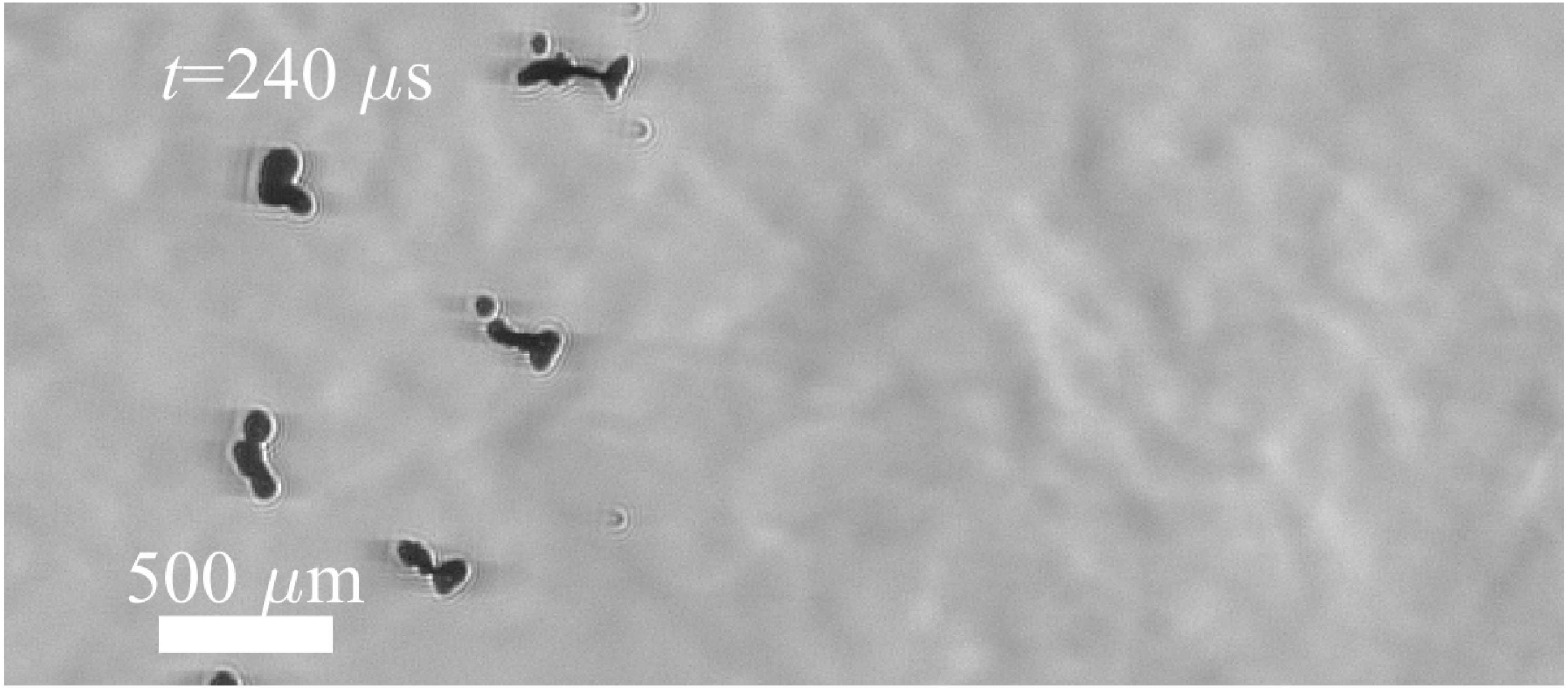

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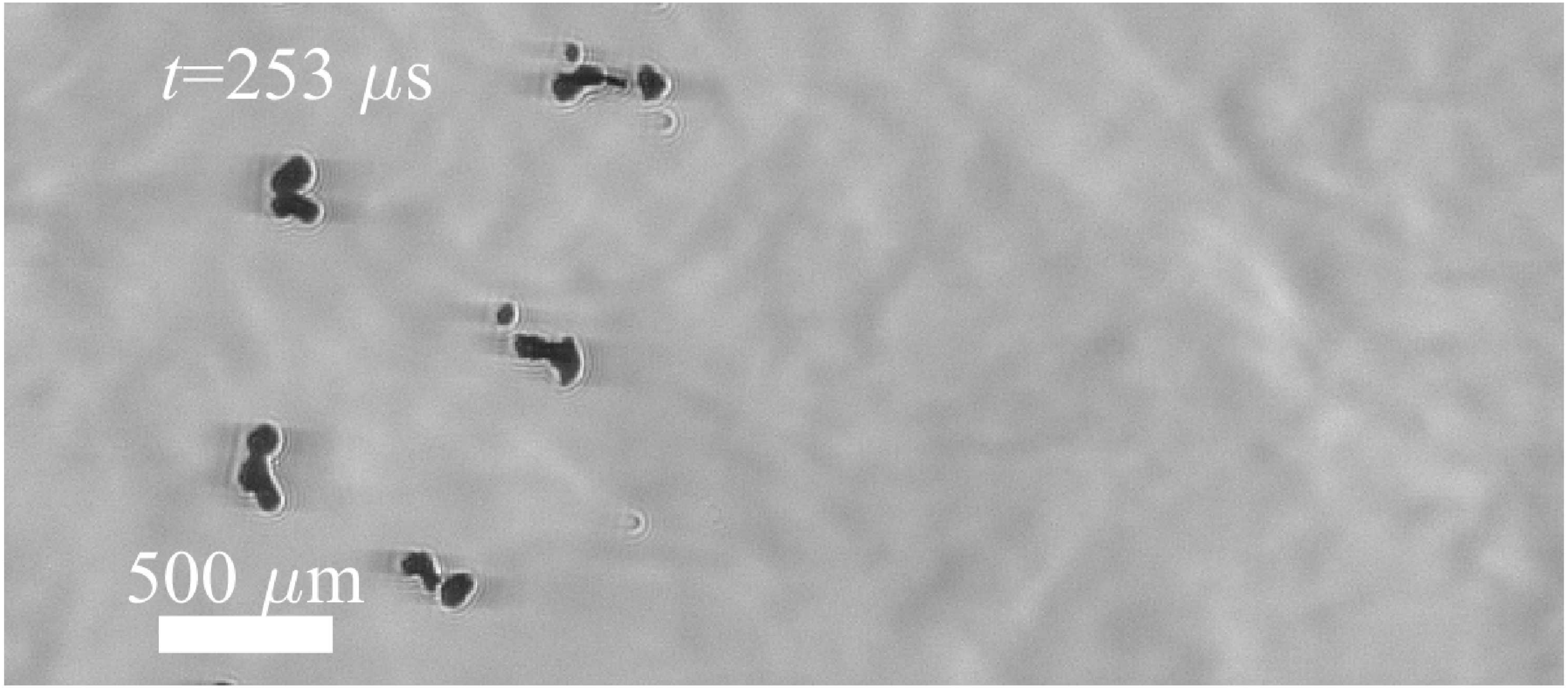

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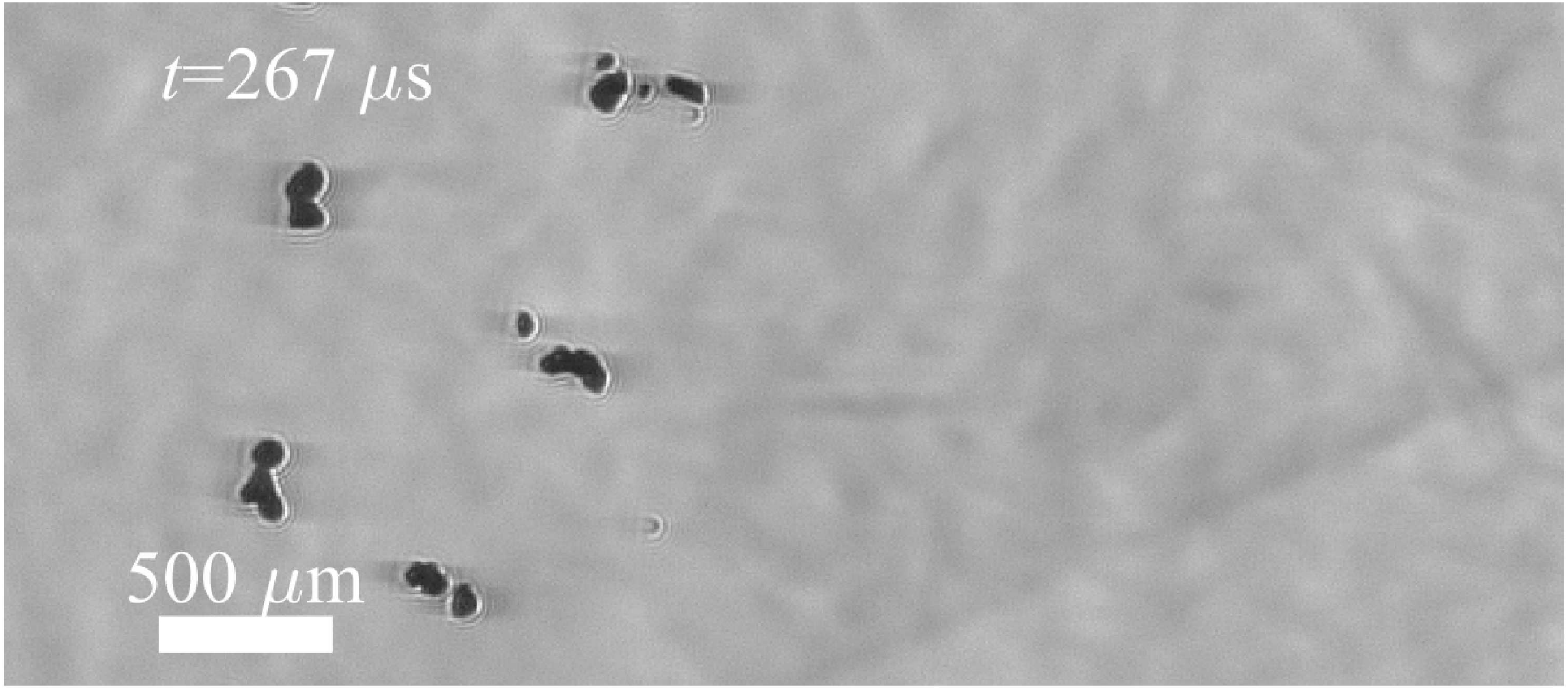

Shot 85 (bullet traveling 4068 ft/s = 1.240 km/s)

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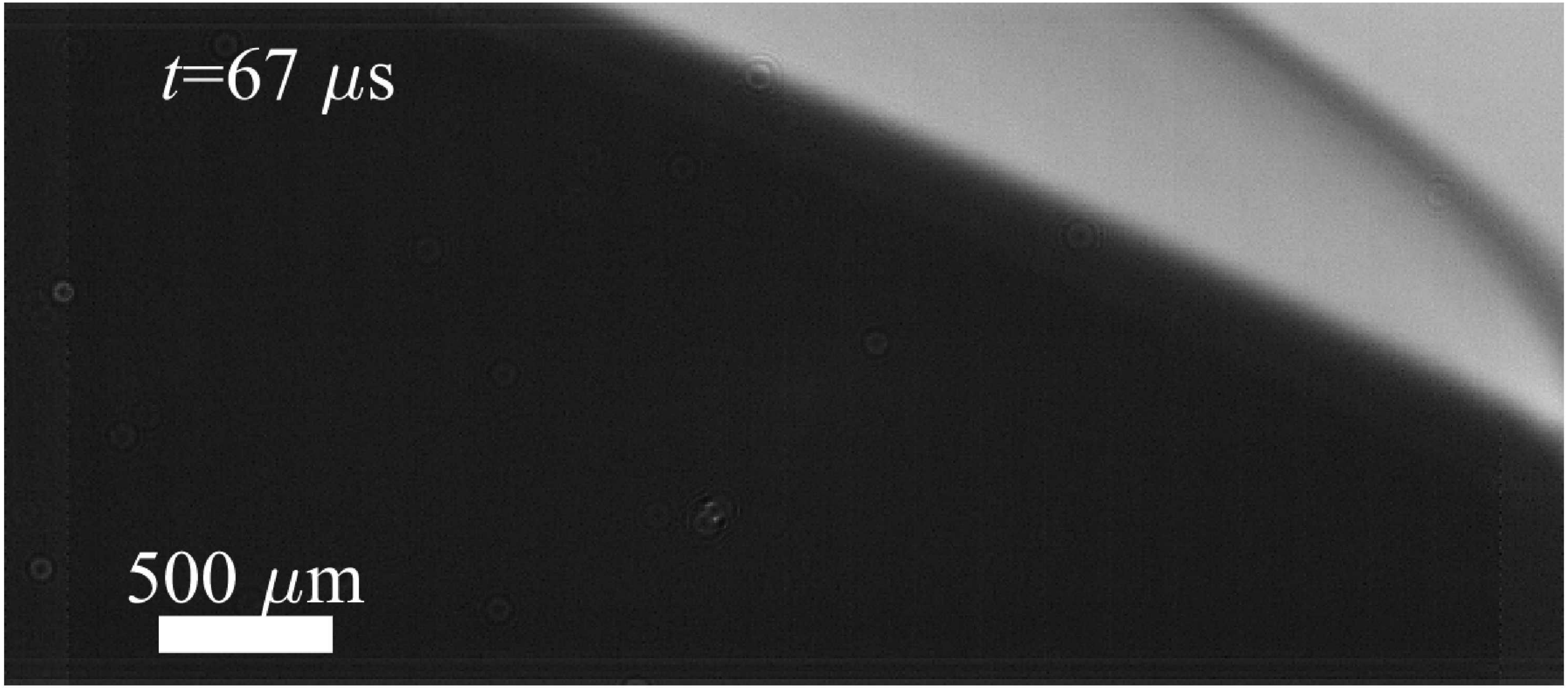

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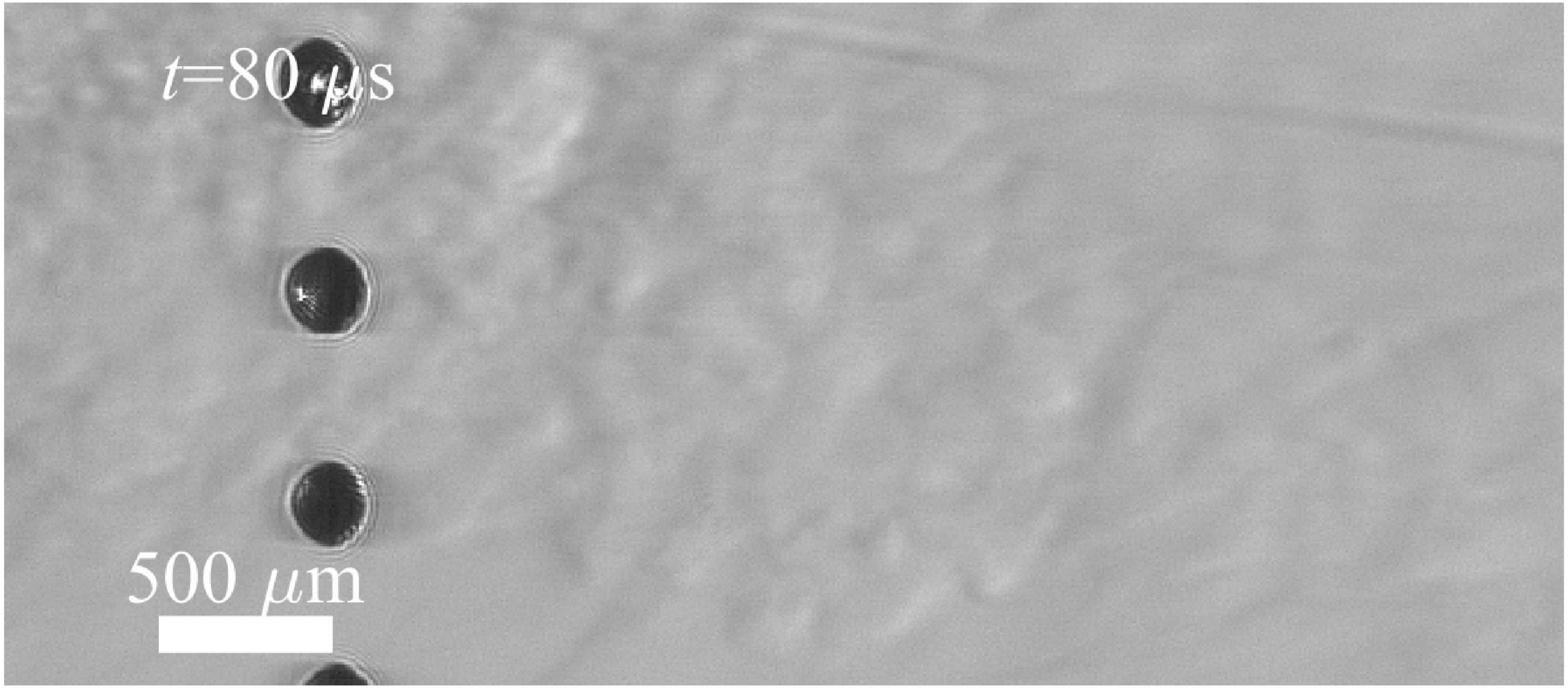

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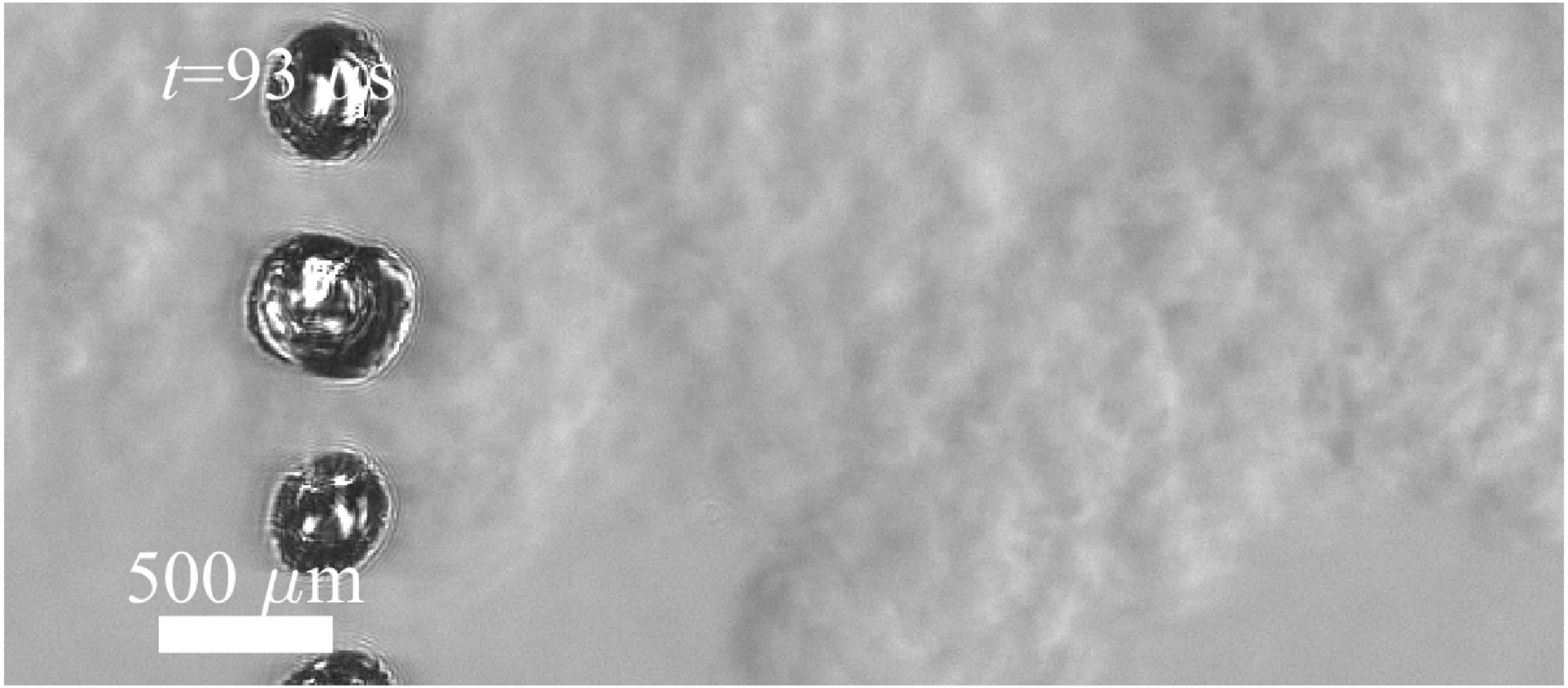

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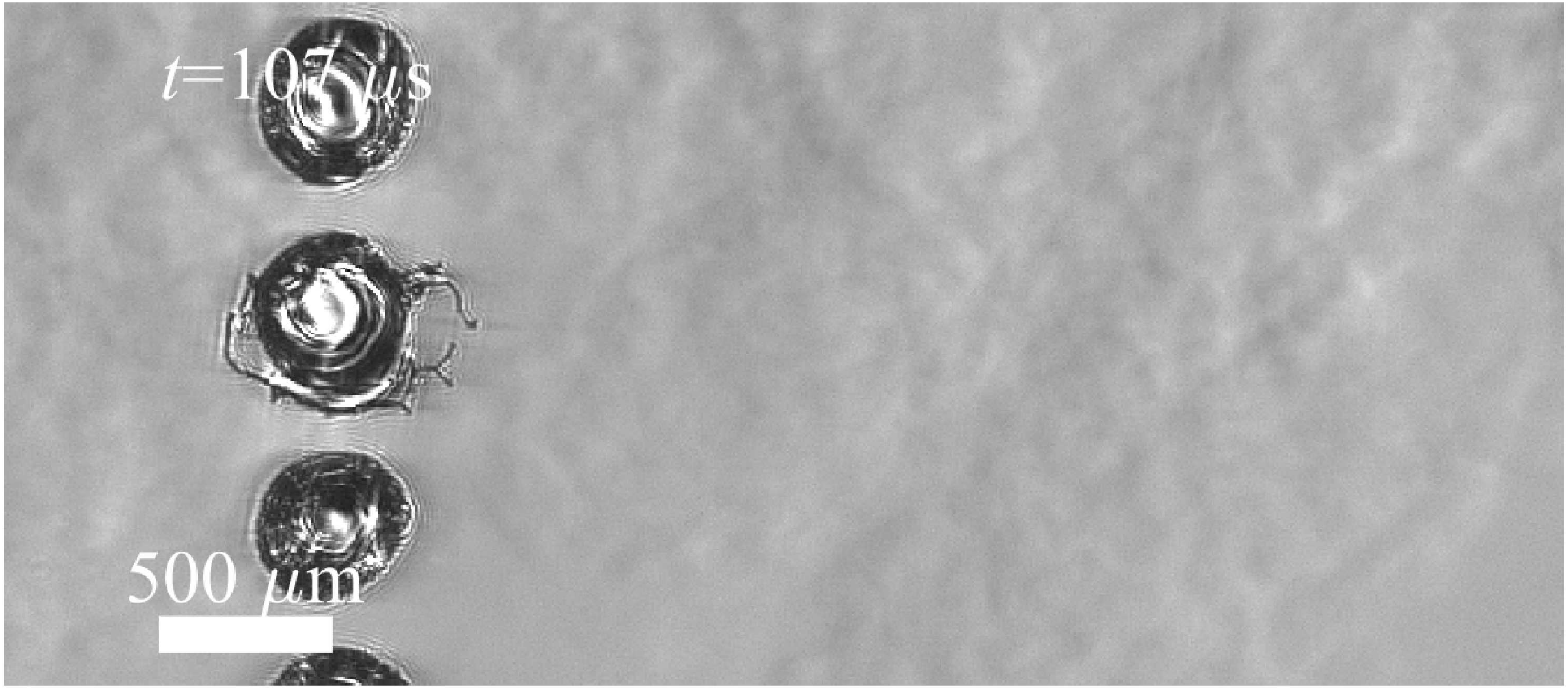

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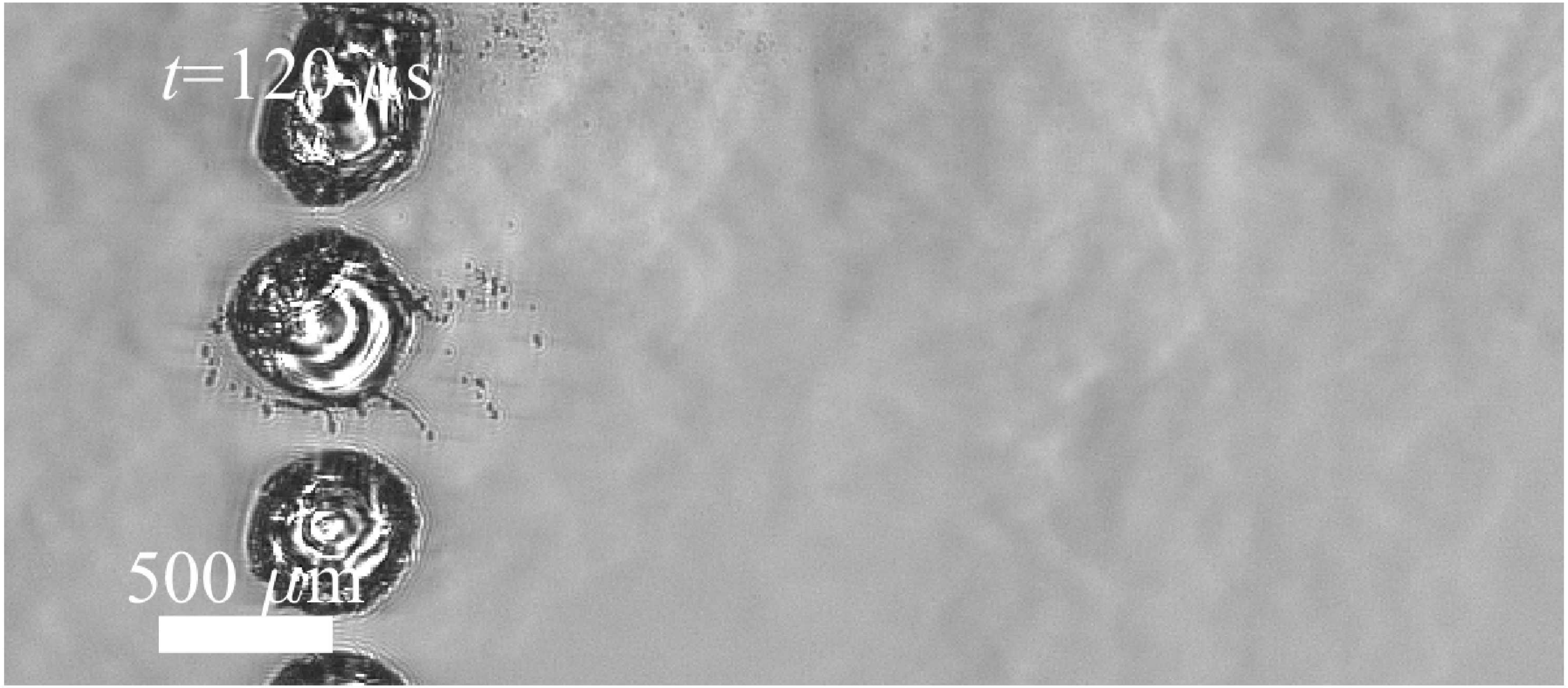

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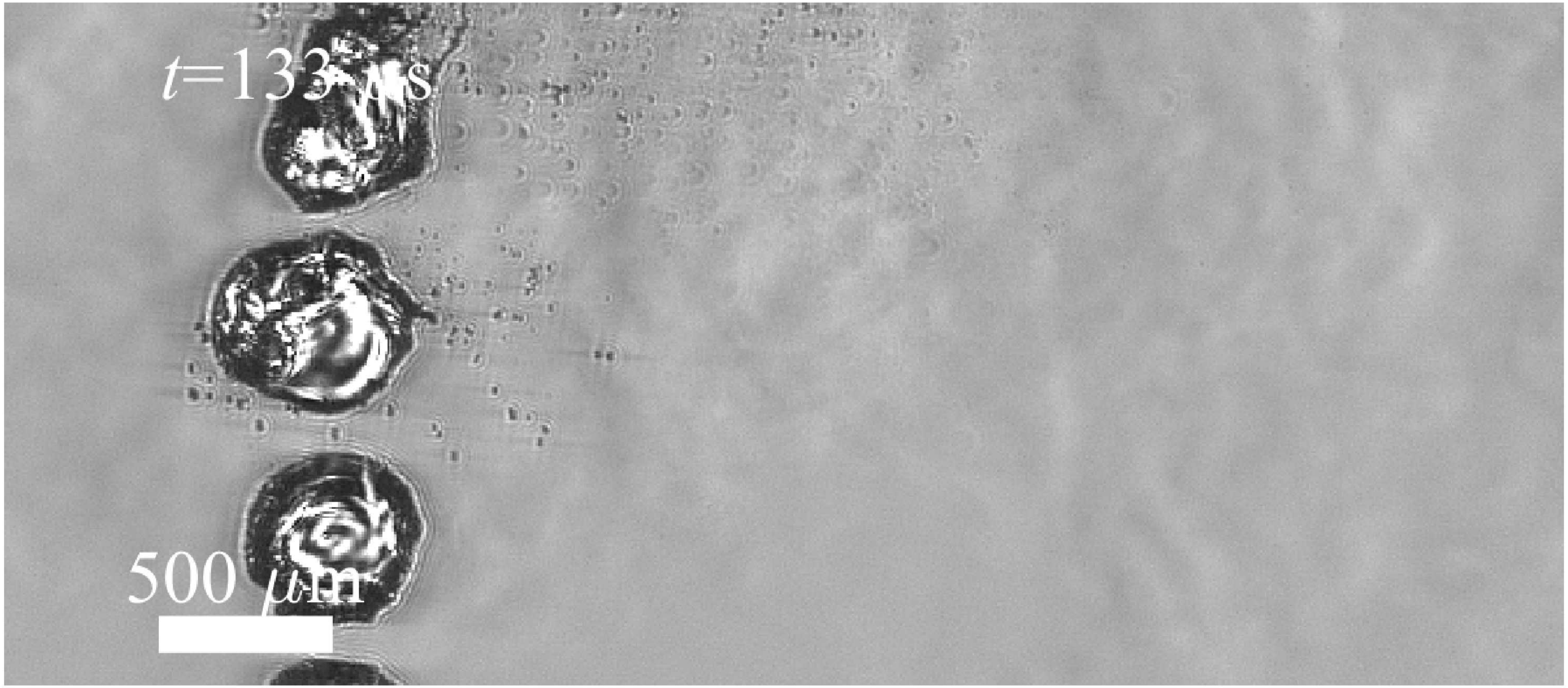

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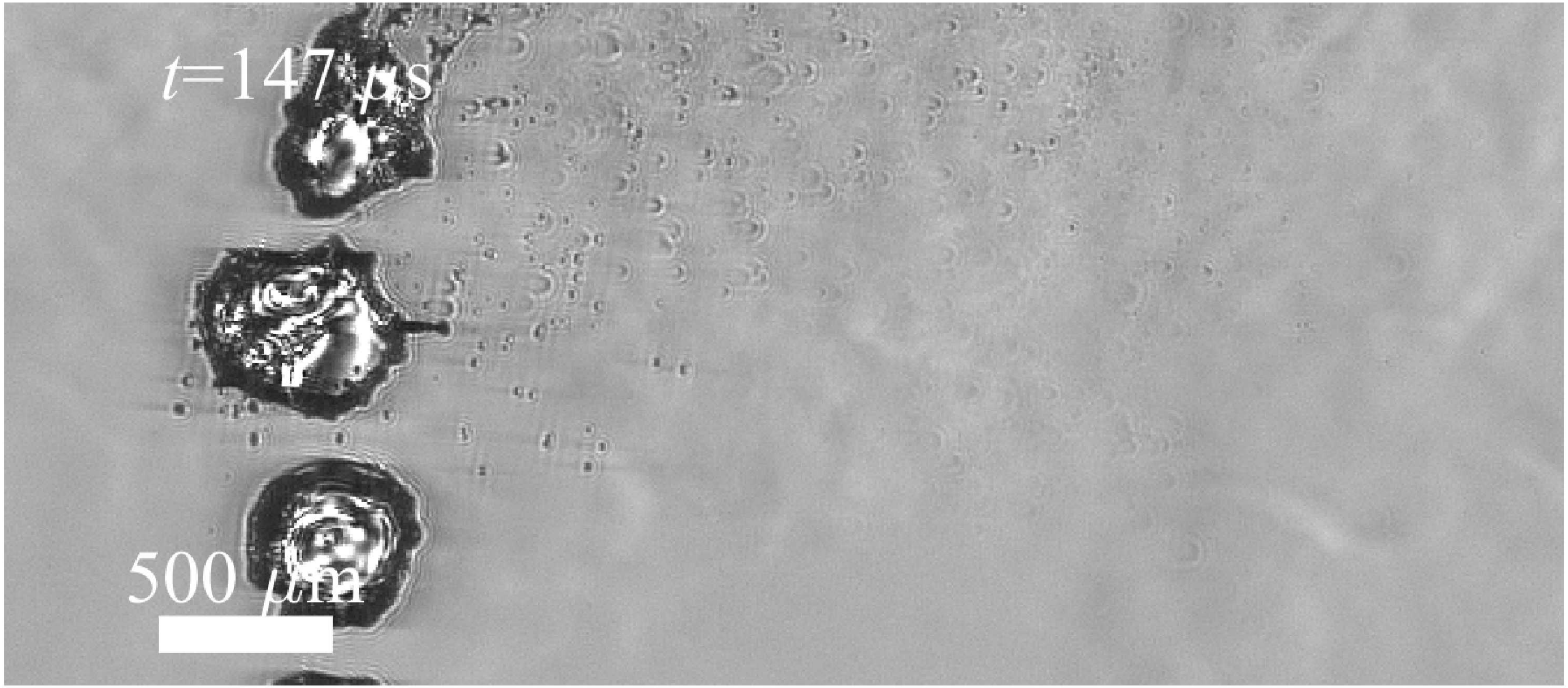

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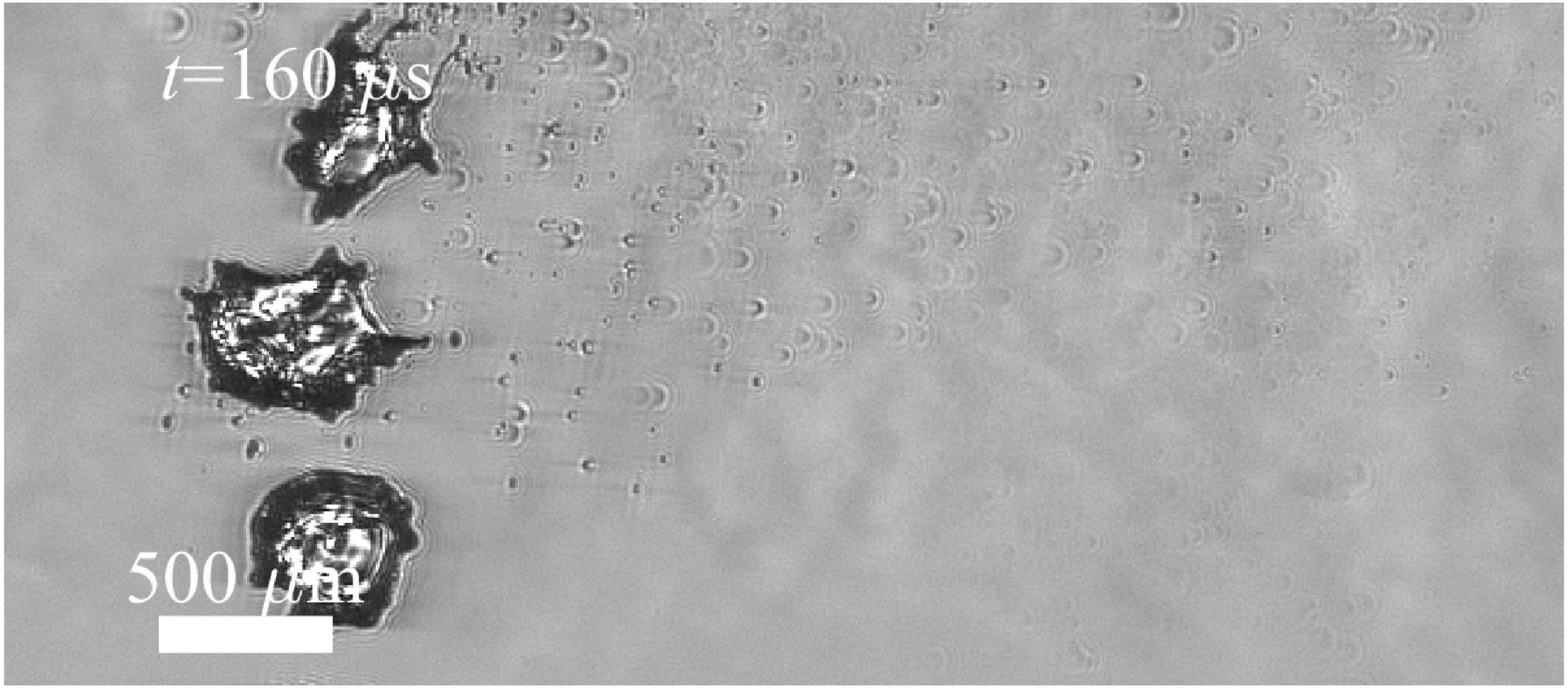

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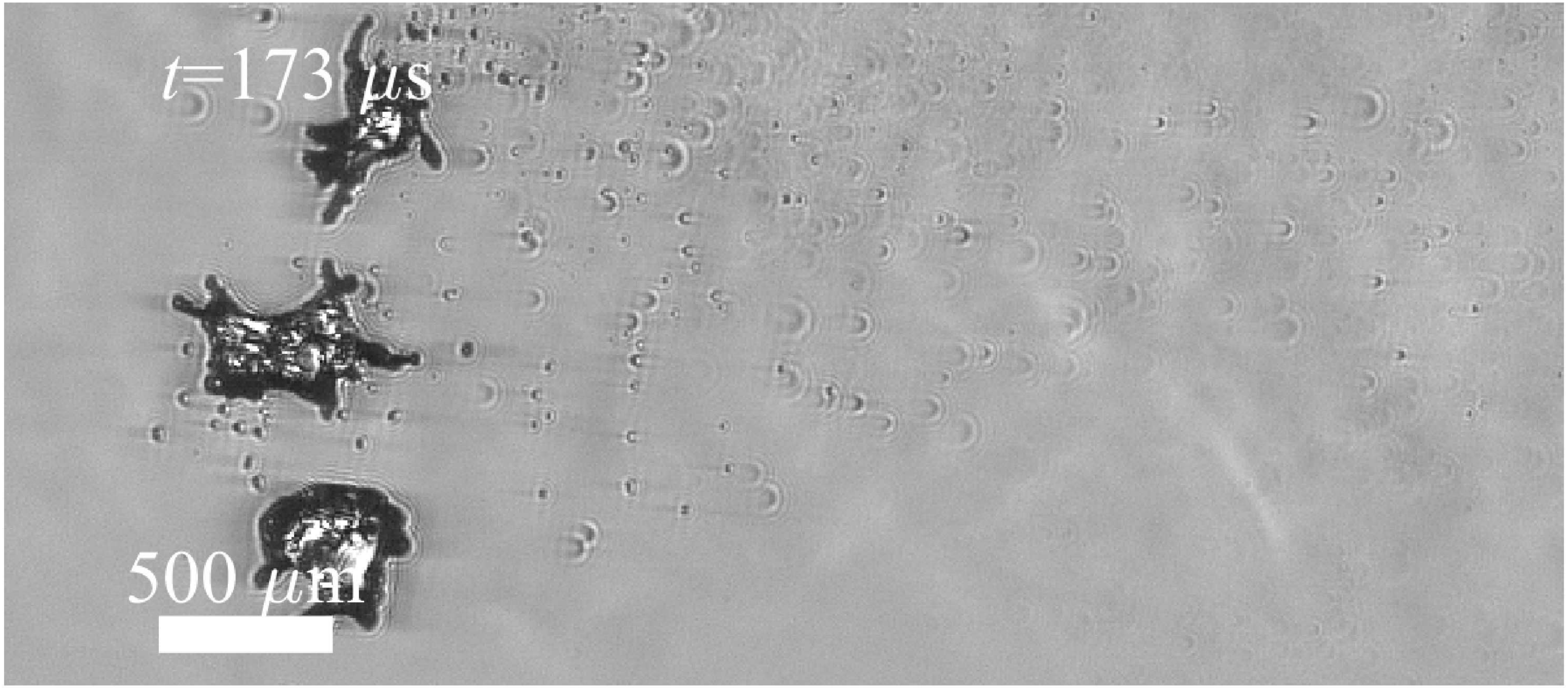

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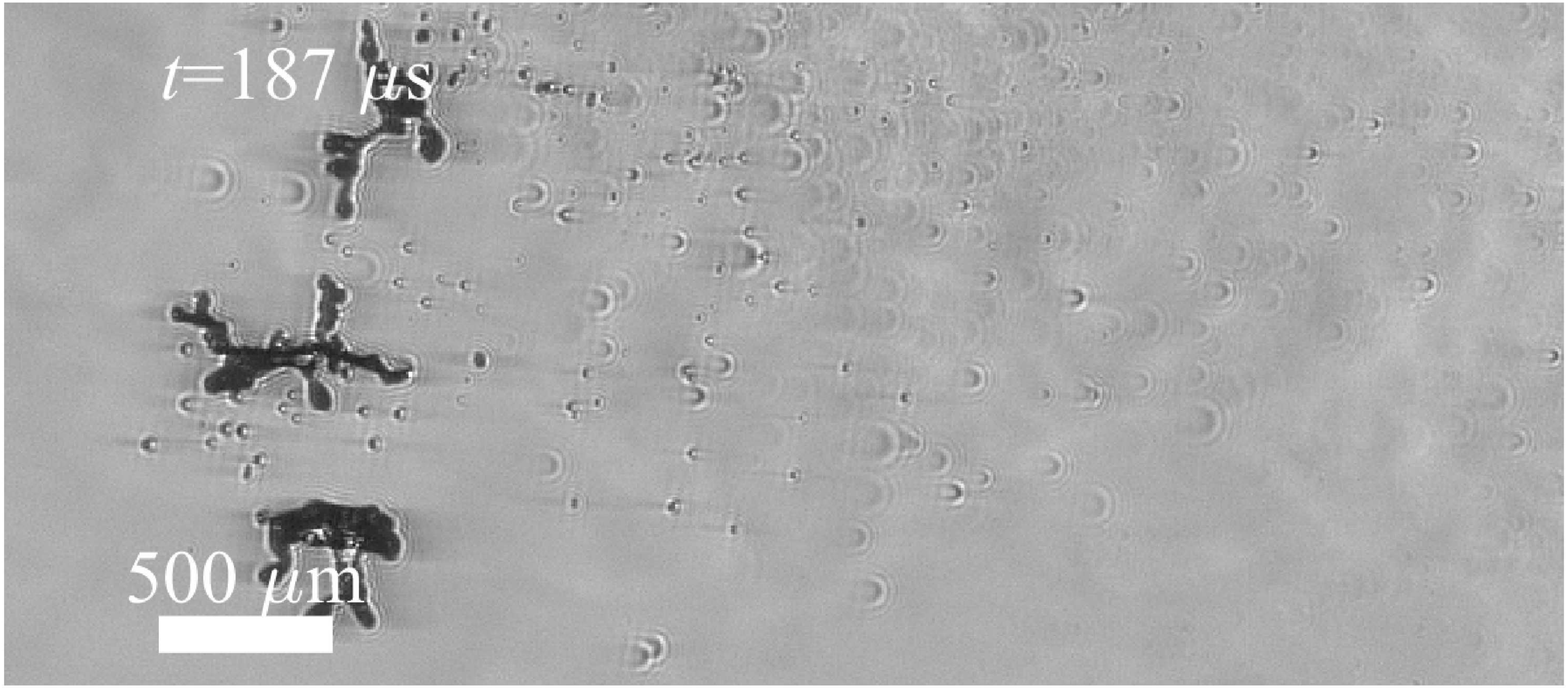

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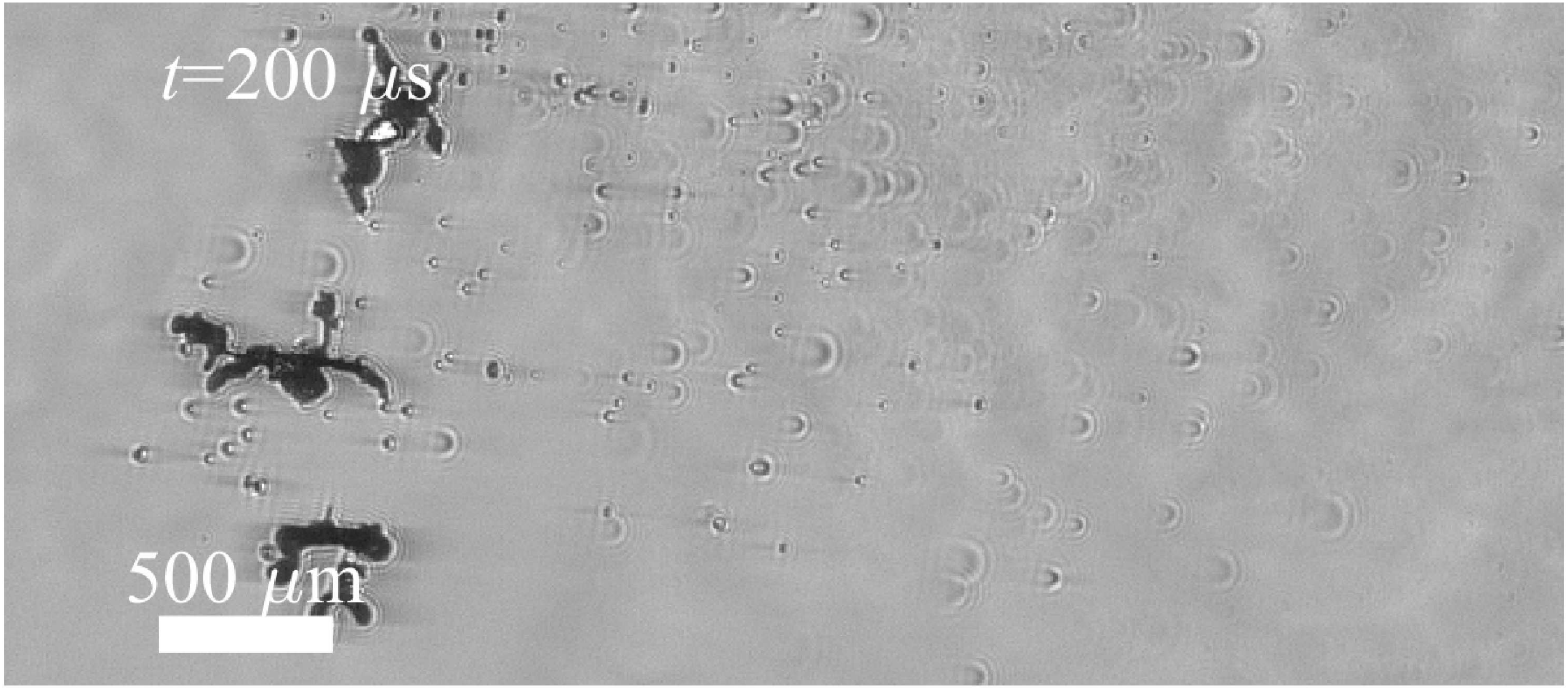

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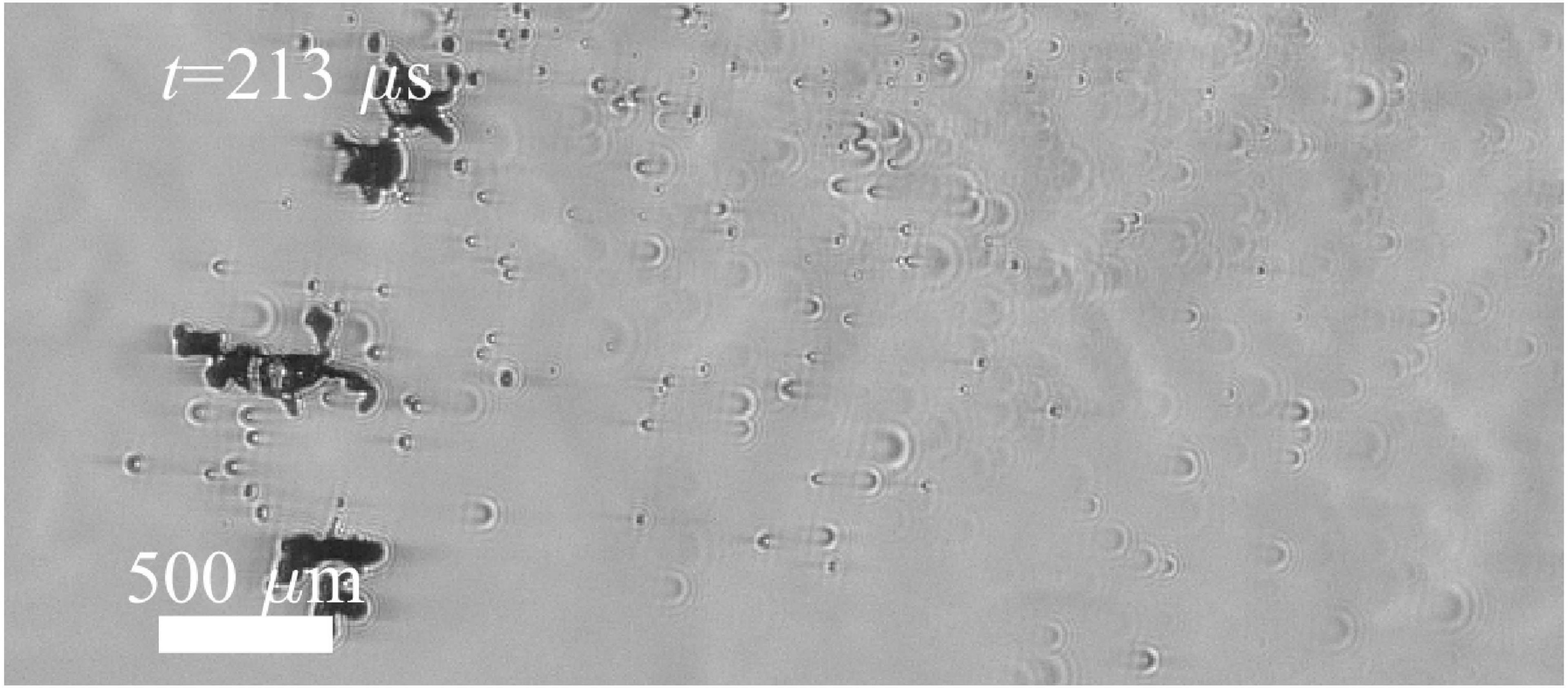

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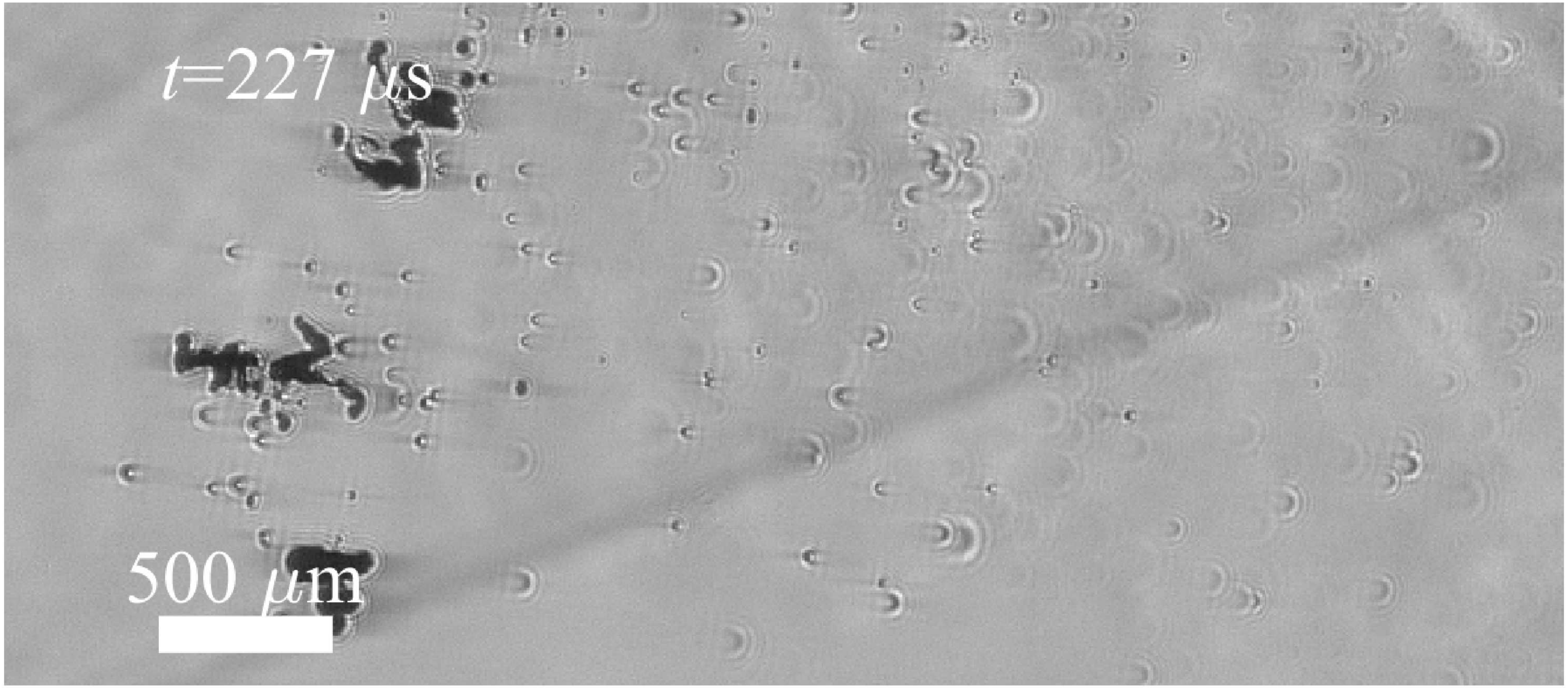

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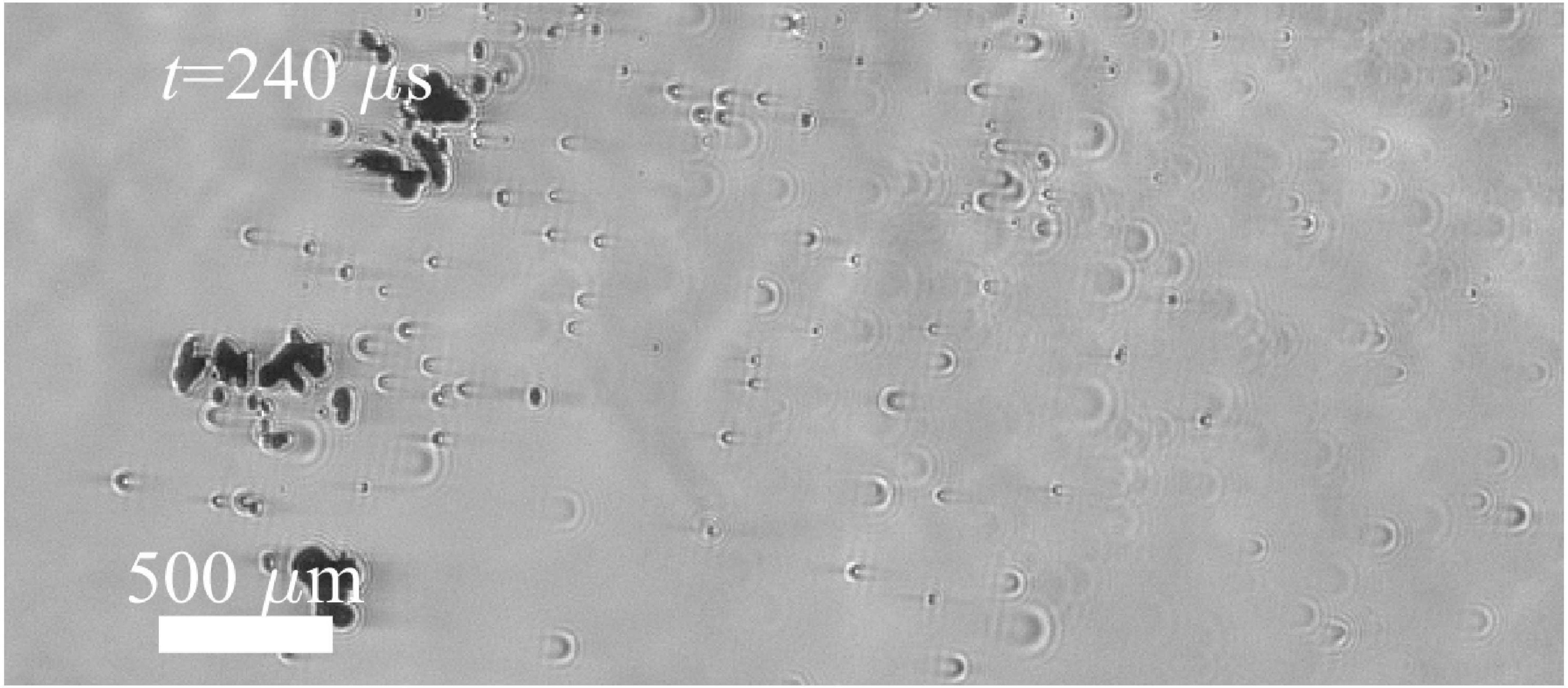

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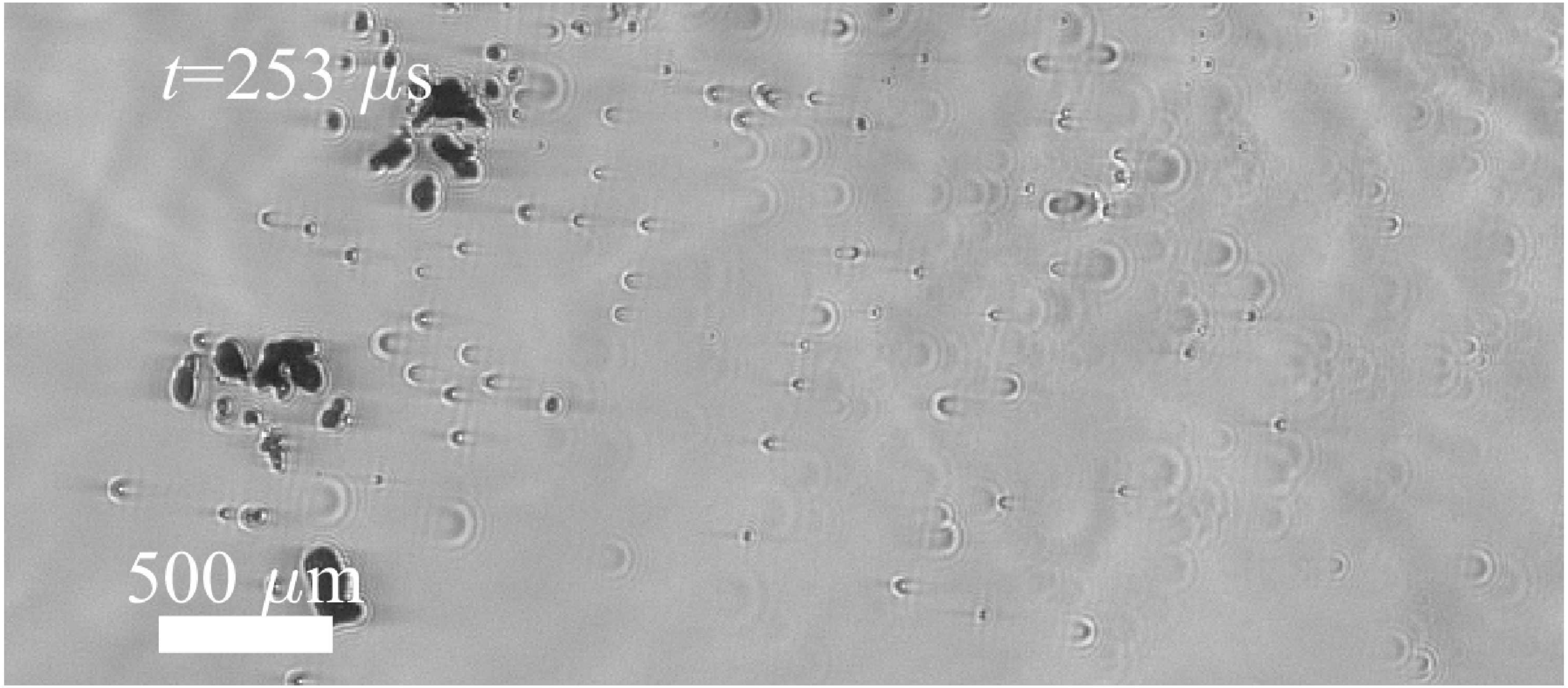

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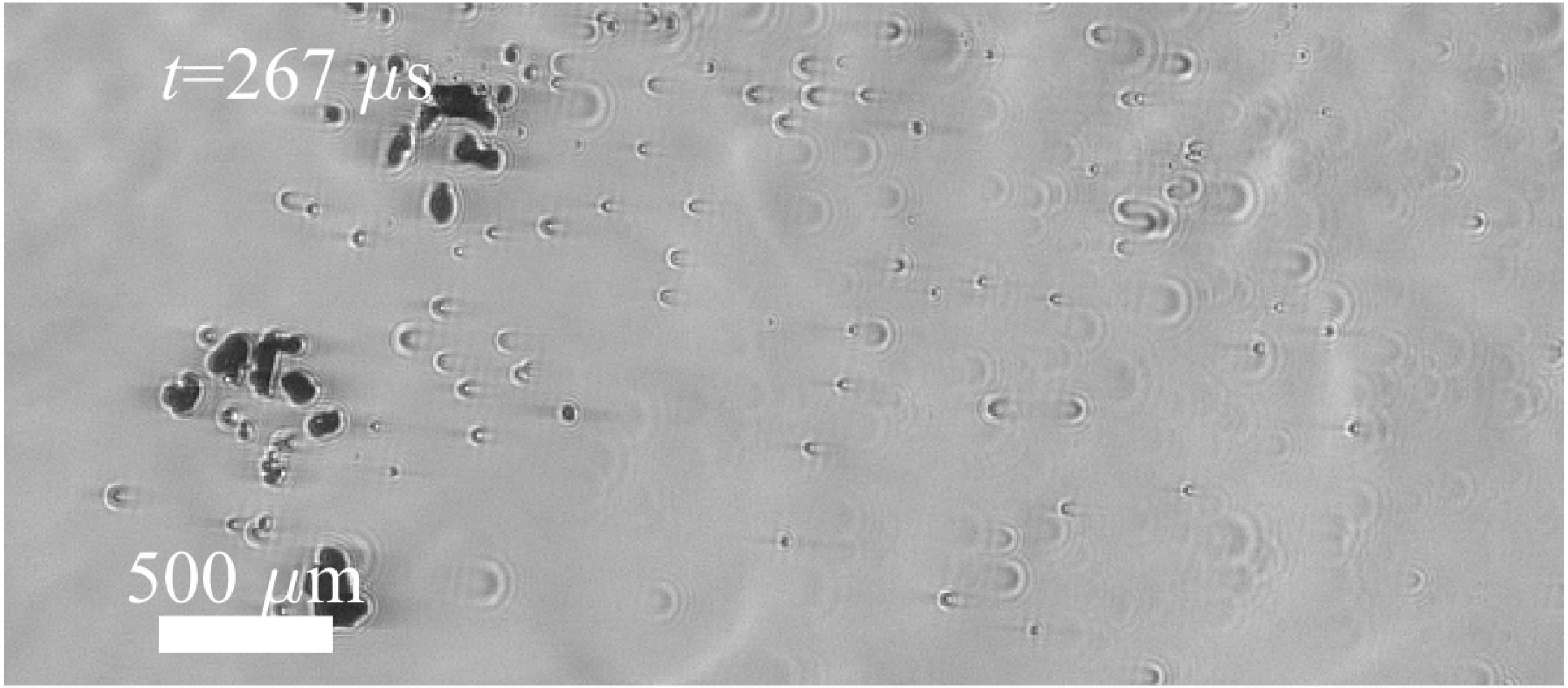
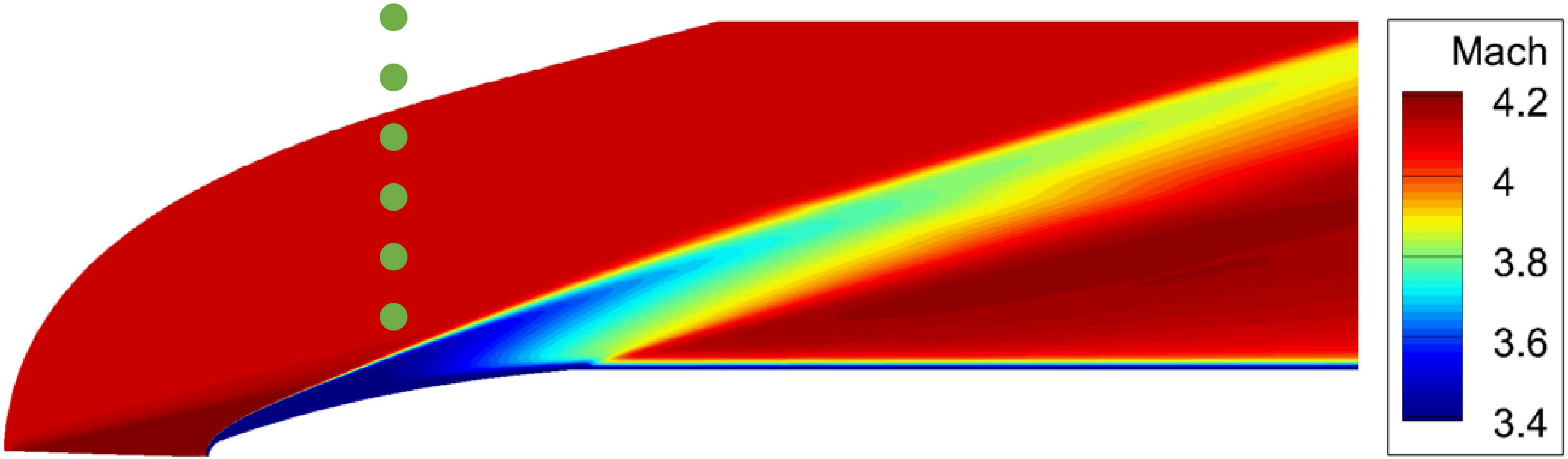


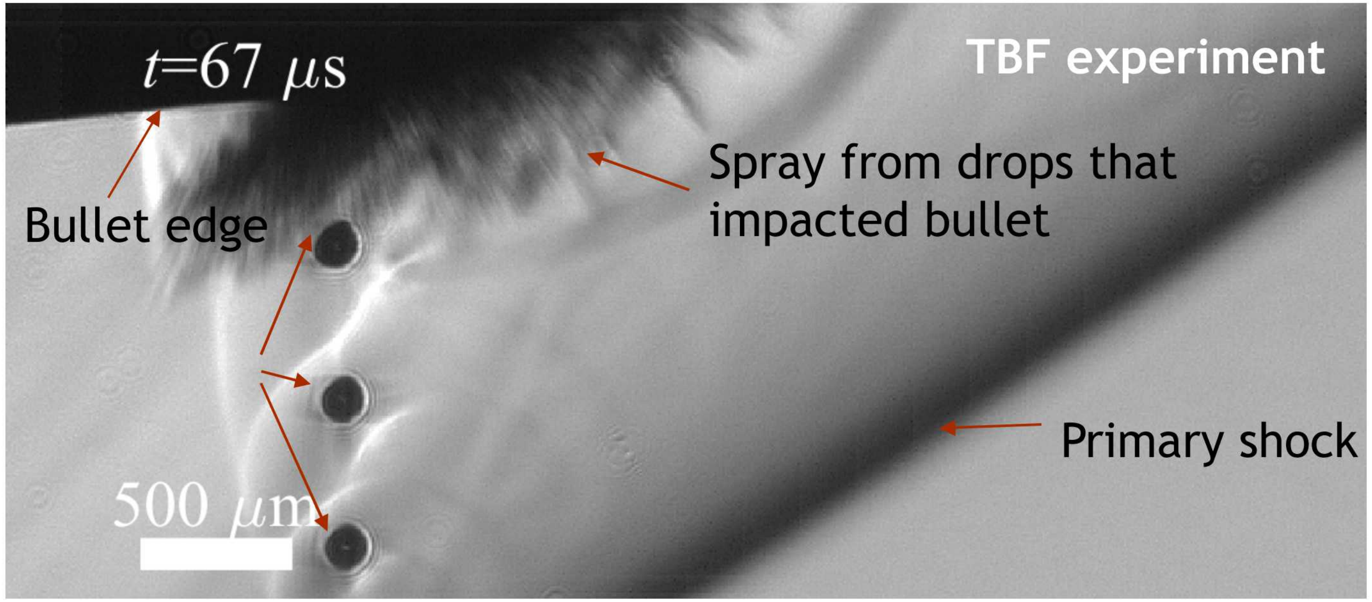
Coming Attractions at TBF

- **None of these droplet effects are included in our current model!**
- **Adding cameras and calibrations to know where the bullet and droplets are in relative space.**
- **Simulations of the bullet tell us what flow the droplets are subjected to.**

This will give us new data on droplet passage through a conical shock that we can integrate into our model.



High-Fidelity Multiphase CFD



Multi-phase CFD code co-developed at the CRF for sharp-interface liquid-gas reconstruction.

Compressible all-Mach formulation makes it ideal for capturing shocks.

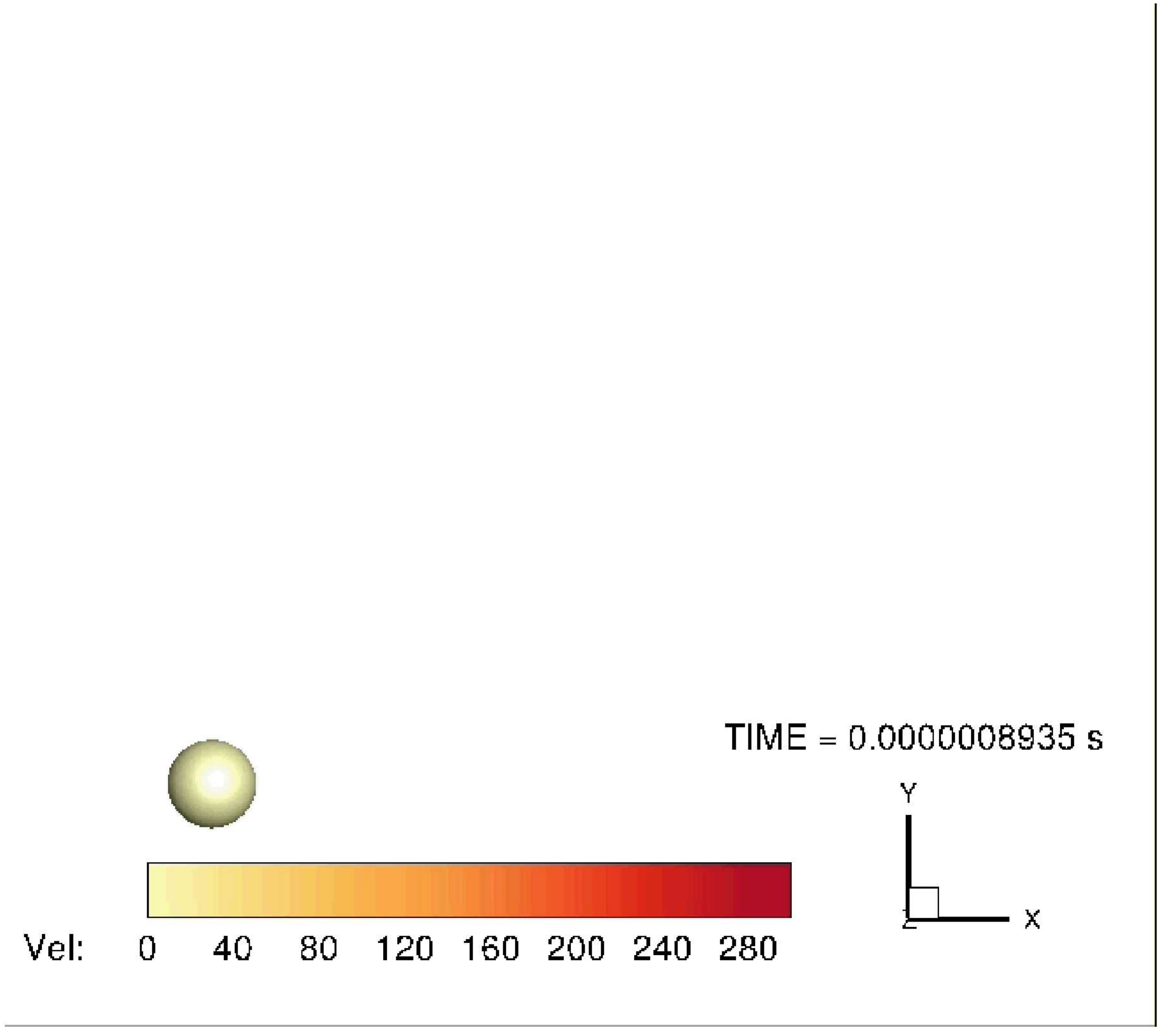
Adaptive mesh refinement targets liquid-gas interface and shock features.

Embedded solid boundary capability makes it possible to directly simulate the shock-rarefaction system of the bullet.

Droplet disintegration is tracked in time, residual mass and trajectory computed from simulation

Full access to 3D shape and to residual droplets distribution

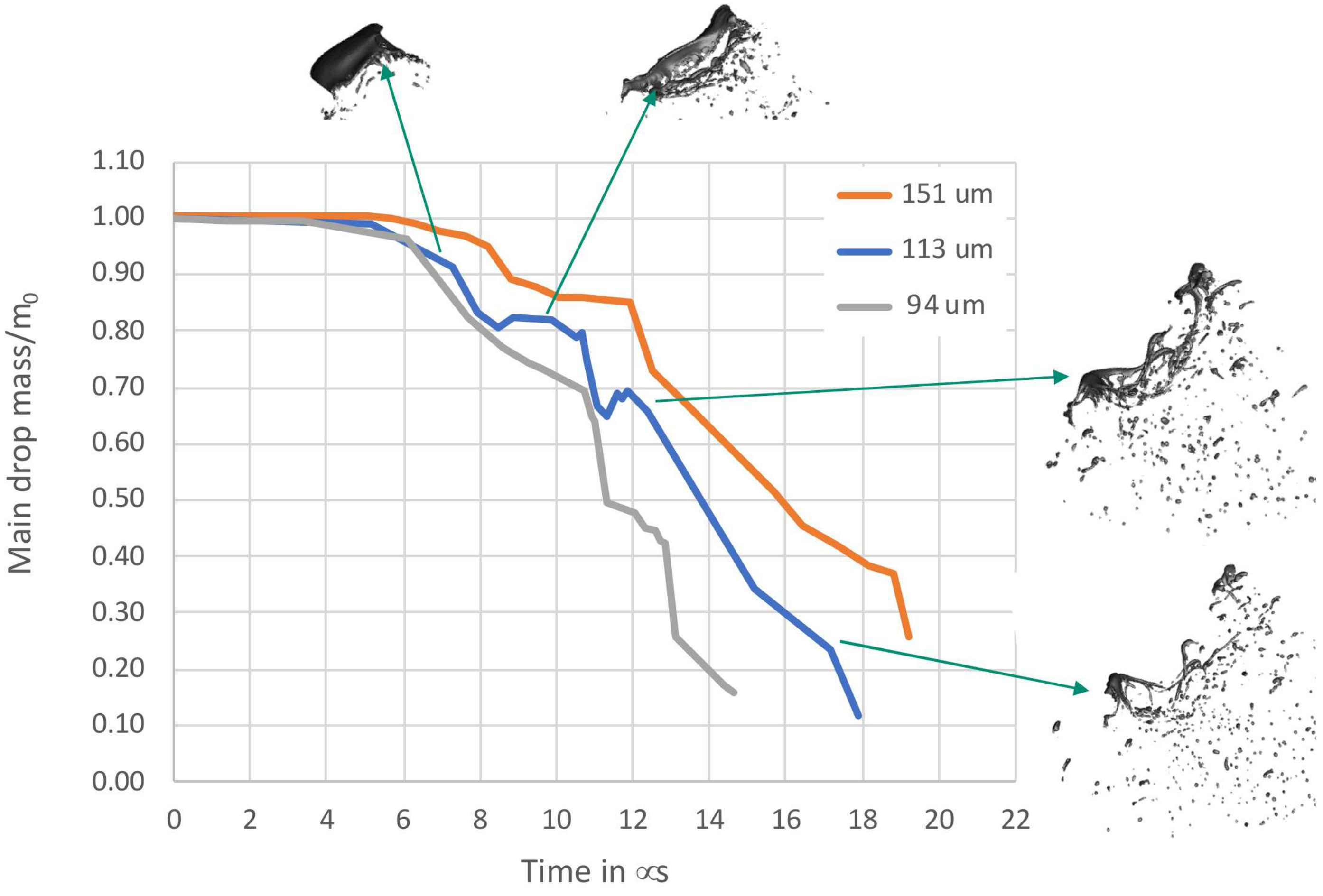
What will we learn from these simulations?

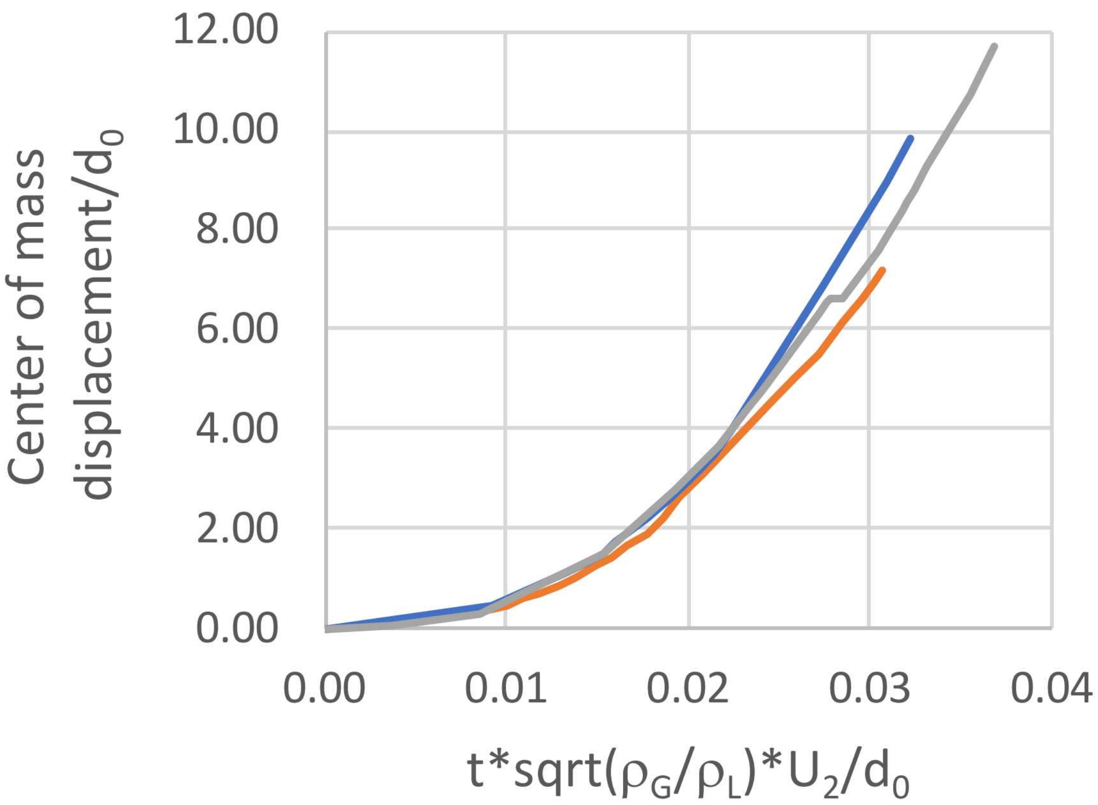


Post-processing of computations:

- **Calculate time to break-up after the passage of the primary shock and compare with existing correlations.**
- **Evaluate trajectories before and after for determination of drag coefficient.**
- **Establish minimum diameter for the droplet to "survive" the passage of the shock with significant mass percentage.**
- ***Compare with TBF data analysis.***

Can we generate new correlations to support the ROM?





These are planar shocks. How will conical shocks change the droplet lifetime?

We will soon have TBF data to add to this.

How will we validate our weather model?

Steve Schneider, a long-time consultant to Sandia, has studied the flight test literature for years in regards to hypersonic transition effects on systems.

We have engaged him to find flight test candidates as validation cases.

We have found perhaps 4-6 reasonable candidates.

All have deficiencies:

- **Limited knowledge of weather conditions.**
  (We have a meteorologist helping us fill the gap probabilistically.)
- **Accelerometer measurements are limited.**
- **Incomplete drawings of vehicle for structural analysis.**

We also are aware of potentially suitable sled track tests upcoming at Holloman AFB.

We will keep looking and thinking about validation. We are aware of this need and the challenges.

The Sandia Team:

Brian Robbins:	**ROM fluids modeler**
Pete Coffin:	**Structural modeler**
Paul Delgado:	**CFD**
Dan Guildenbecher:	**Multiphase experiments**
Kyle Daniel:	**Multiphase experiments**
Marco Arienti:	**High-fidelity multiphase simulations**
Everett Wenzel:	**High-fidelity multiphase simulations**
Steve Beresh:	**Takes credit for everyone else's hard work**

This problem is extremely daunting and we are eager to collaborate with other national teams working the same topic!