

# Experimental Study of a Strongly Shocked Gas Interface with Visualized Initial Conditions

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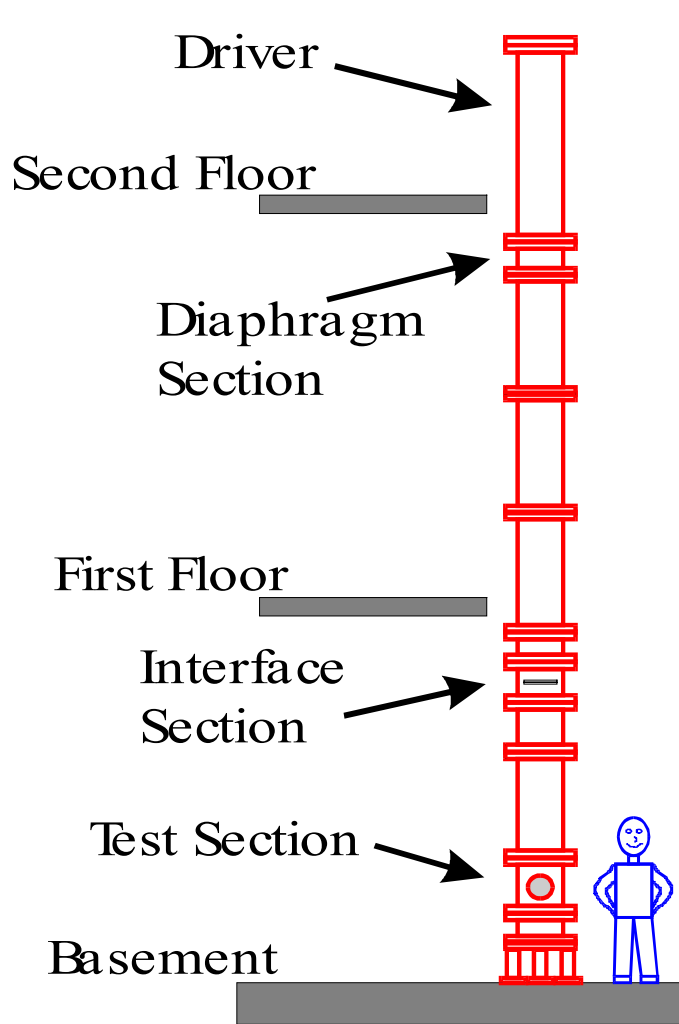
# Outline

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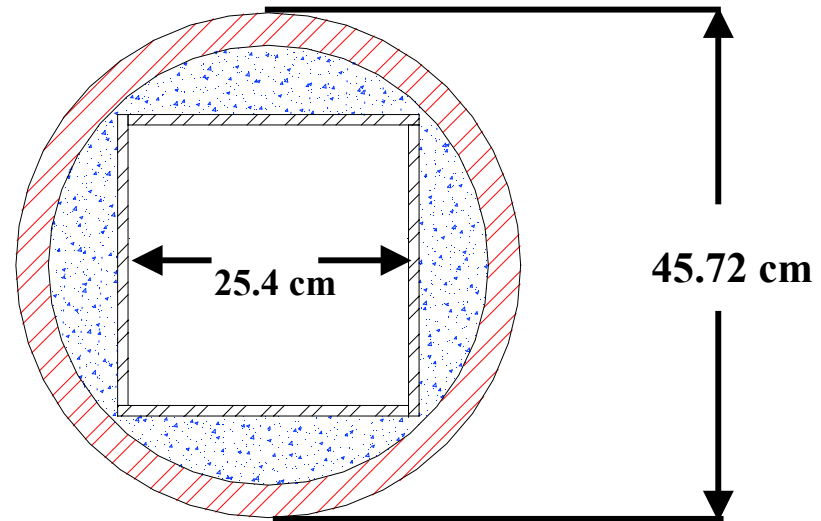
- University of Wisconsin Shock-Tube Laboratory (WiSTL)
- Interface preparation
- Shocked interfaces
- Comparisons with non-linear theories
- Conclusions



# WiSTL (Wisconsin Shock Tube Laboratory)



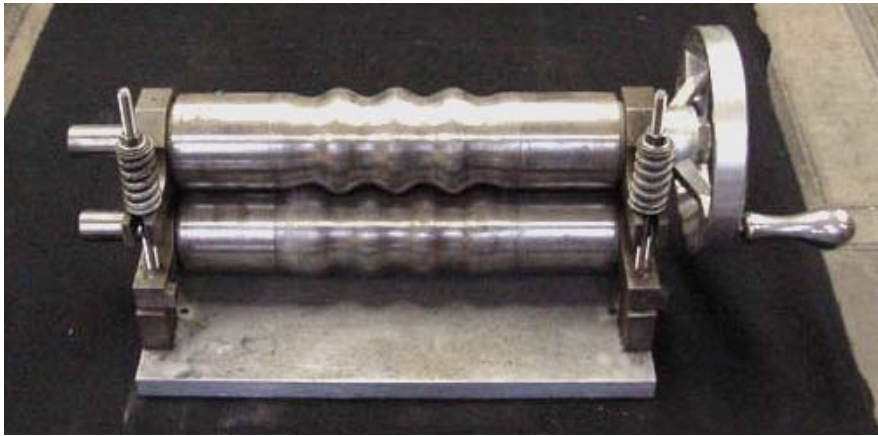
- Vertical Orientation
- Large Internal Square Cross-Section (25 cm square)
- Total Length=9.2 m
- Driven Length=6.8 m
- Structural Capacity 20 Mpa
- Modular Construction



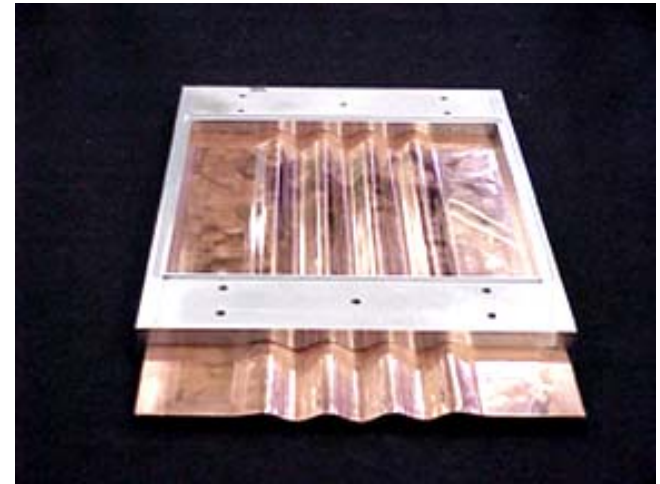
# Interface Preparation

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- Use of a retractable metal plate formed into a sinusoidal shape
- Copper plate, 0.6 mm thick
- Plastic deformation by rolling operation
- Sine wave parameters:
  - Amplitude = 3.18 mm
  - Wavelength = 38.1 mm
  - $\eta_0/\lambda = 0.083$



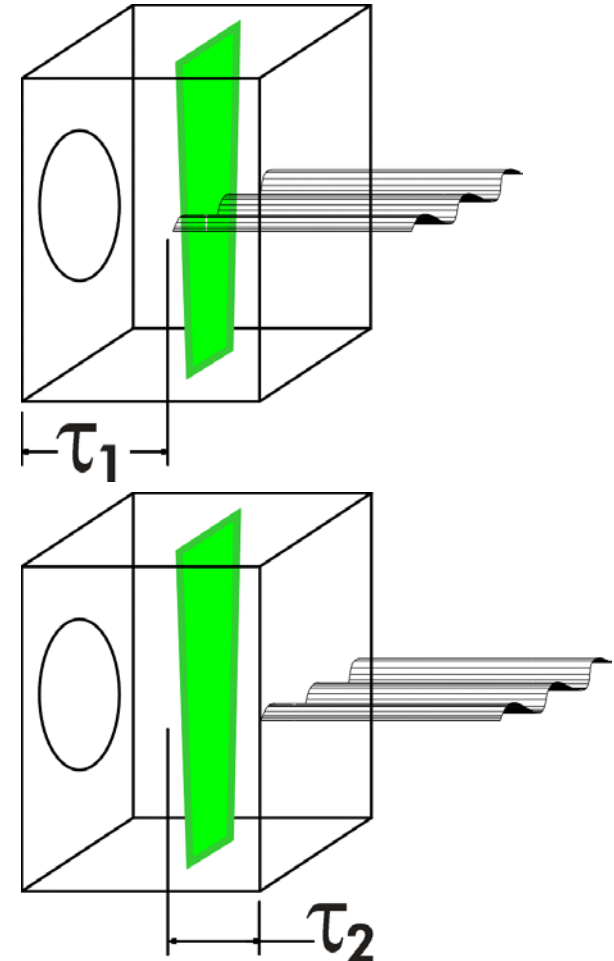
Rollers



Formed plate

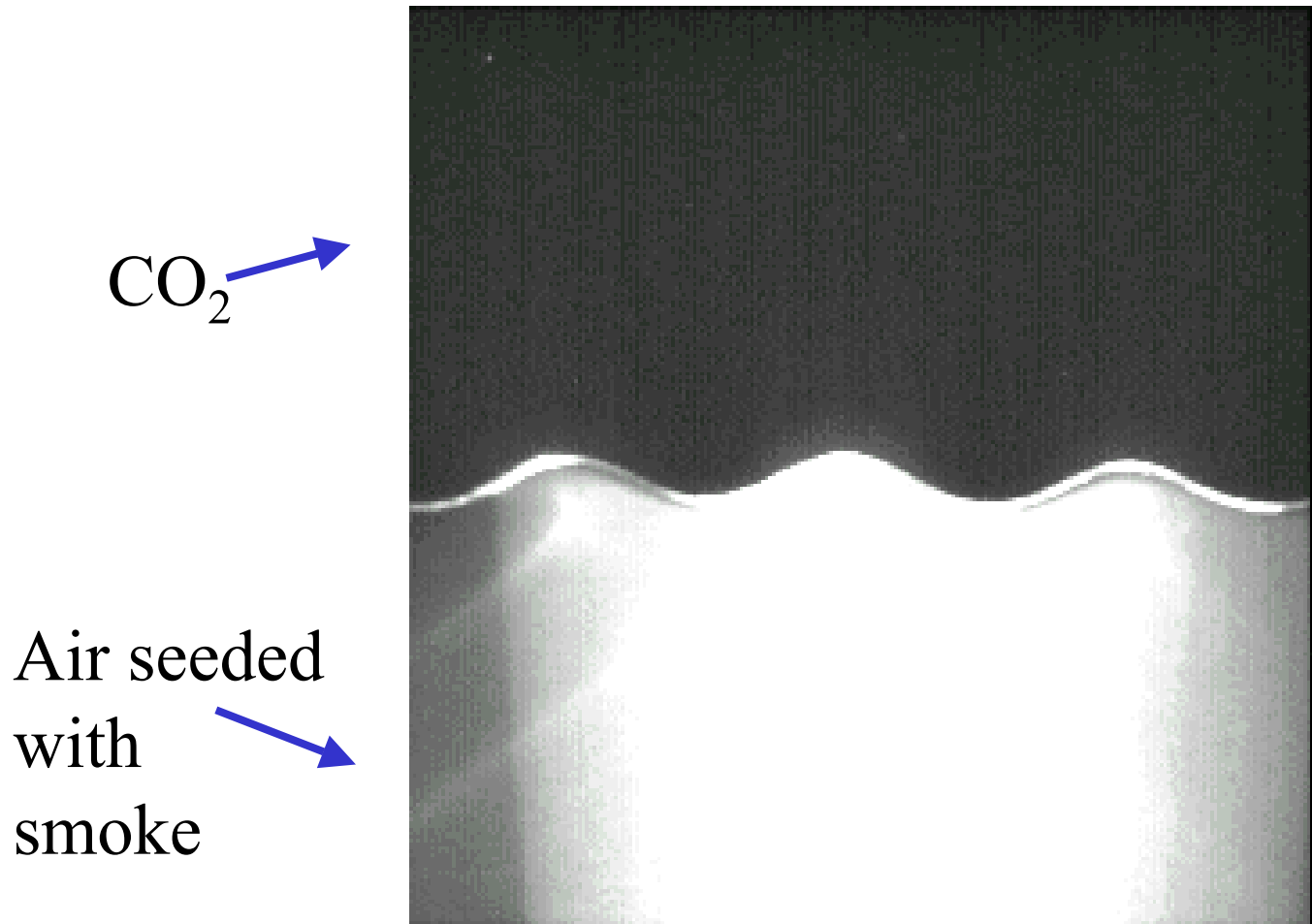
# Study of initial conditions

- $P_{\text{initial}} = 1 \text{ atm}$ ,  $T_{\text{initial}} = 298 \text{ K}$
- Ar-ion laser @  $\lambda=514$  and  $488 \text{ nm}$ , CW
- Planar Mie scattering visualization
- CCD camera:  $256 \times 256$  pixel array, 8 bit/pixel
- Two-stage retraction ( $\tau_1 \sim 250 \text{ ms}$ ,  $\tau_2 \sim 80 \text{ ms}$ )

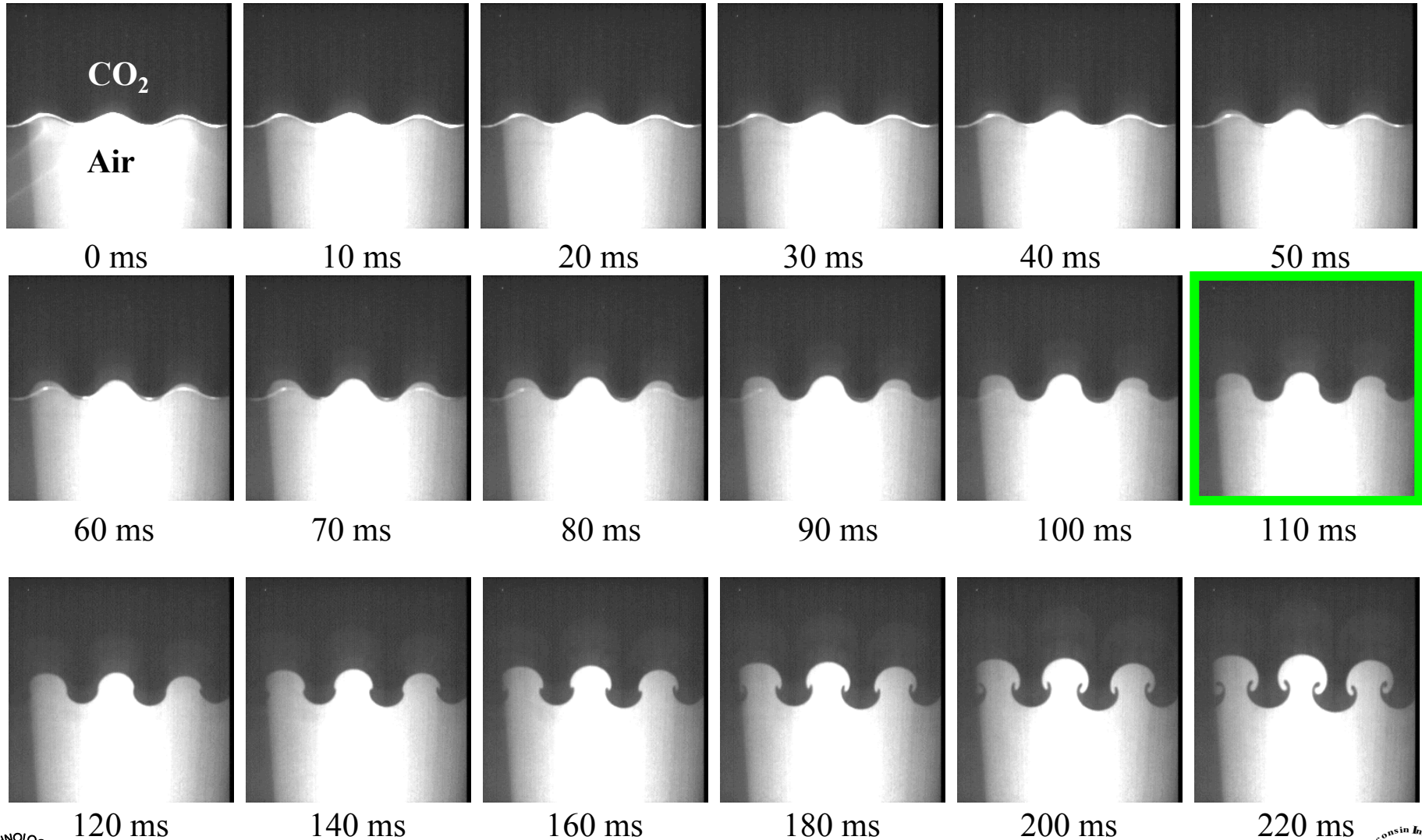


# RT Unstable Interface (CO<sub>2</sub>/Air)

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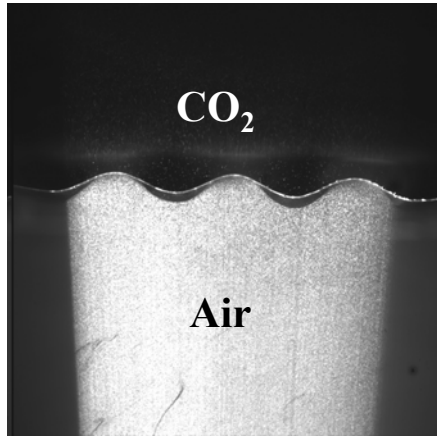


# Desired $\tau_{RT} < 120$ ms for RM Initial Condition

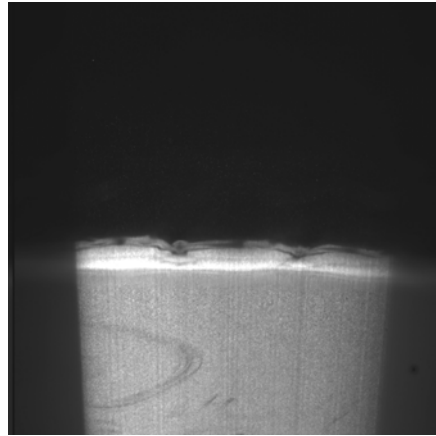


# R-M instability visualization results

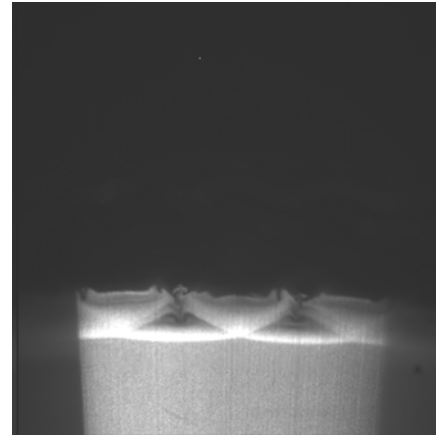
- $\text{CO}_2/\text{Air}$ ,  $A_{\text{post}} = 0.246$ ,  $A_{\text{pre}} = 0.206$
- Very early interaction of the  $M=3.06$  shock wave with the sinusoidal interface
- Development of phase reversal (heavy/light configuration)



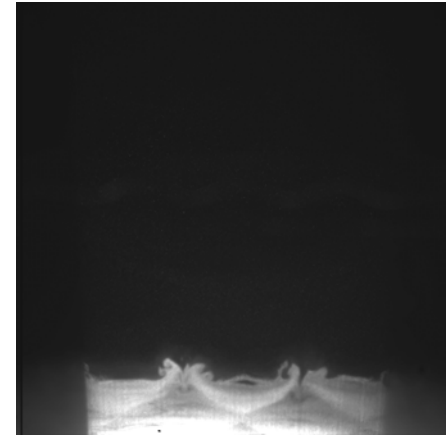
(a)



(b)



(c)

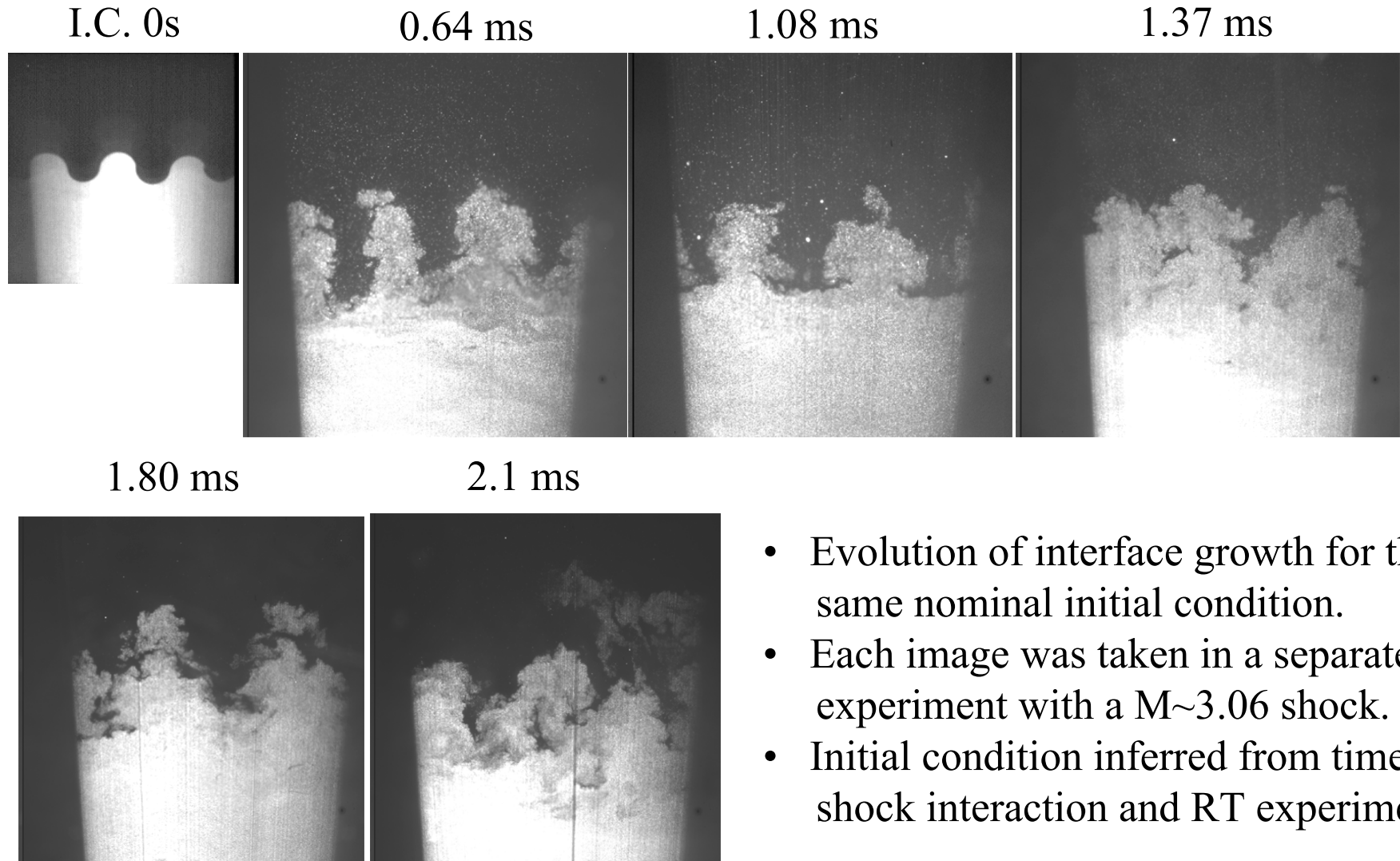


(d)

- (a): Pre-shocked interface (Note the location of peaks and troughs)
- (b): Shocked interface  $\sim 5 \mu\text{s}$  after initial shock acceleration
- (c): Shocked interface  $\sim 36 \mu\text{s}$  after initial shock acceleration
- (d): Shocked interface  $\sim 39 \mu\text{s}$  after initial shock acceleration



# R-M instability visualization results (Cont'd)



- Evolution of interface growth for the same nominal initial condition.
- Each image was taken in a separate experiment with a  $M \sim 3.06$  shock.
- Initial condition inferred from time of shock interaction and RT experiments.

# Experiments: Image Analysis

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- Images
  - Initial condition: 3 peaks, 2 troughs
  - Shocked image: 1-4 peaks, 1-3 troughs
  - Median filter
  - Excess noise removed in driven and test gases manually
  - Convert to black and white, then apply Sobel operator to detect edge

- Perturbation amplitude:

$$\eta = \frac{1}{2} (\bar{P}_{PIX} - \bar{V}_{PIX} - 1) P_{DIM}$$

$\bar{P}_{PIX}$  = average pixel row number of perturbation peaks

$\bar{V}_{PIX}$  = average pixel row number of perturbation valleys

$P_{DIM}$  = pixel dimension (mm/pixel)

- Error less than 2 pixels: 0.8 mm for initial condition, 0.4 mm for shocked interface

# Analytic theories

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Richtmyer (1960) impulsive model:  $\eta(t) = k[u_p]A\eta_0 t$

Sadot *et al.* (1998) nonlinear theory:  $\left(\frac{d\eta}{dt}\right) = \left(\frac{d\eta}{dt}\right)_{LIN} \left(\frac{1+Bt}{1+Dt+Et^2}\right)$

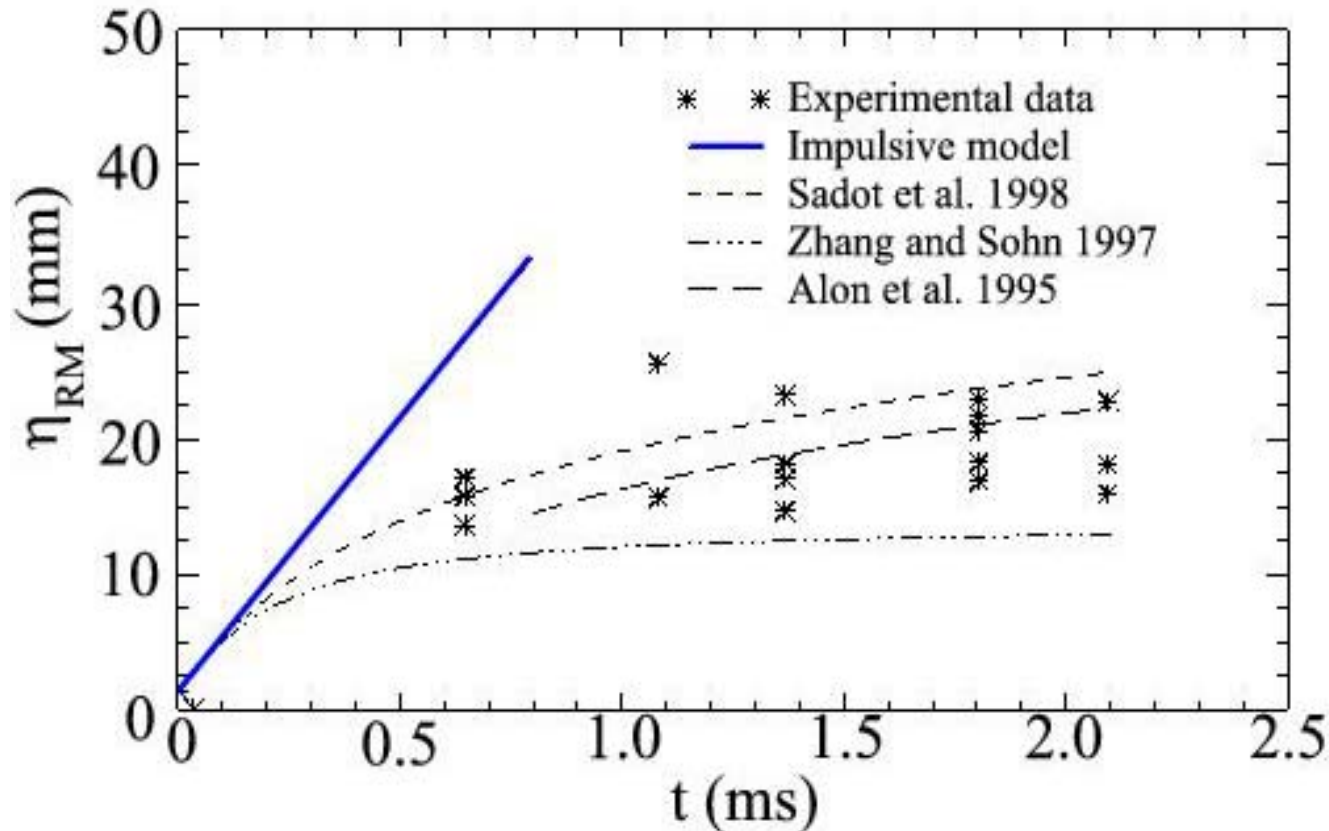
$$D_{b/s} = (1 \pm A') \left(\frac{d\eta}{dt}\right)_{imp} k \quad E_{b/s} = [(1 \pm A') / (1 + A')] \times (1 / 2\pi C) \left(\frac{d\eta}{dt}\right)_{imp}^2 k^2$$

$$C = 1/2\pi \quad \text{for low } A'$$

Zhang and Sohn (1997) nonlinear theory:

$$\left(\frac{d\eta}{dt}\right)_{total} = \frac{\left(\frac{d\eta}{dt}\right)_{lin}}{1 + \left(\frac{d\eta}{dt}\right)_{lin} \eta_0' k^2 t + \max\{0, \eta_0'^2 k^2 - A'^2 + 1/2\} \left(\frac{d\eta}{dt}\right)_{lin}^2 k^2 t^2}$$

# Comparison with Theories



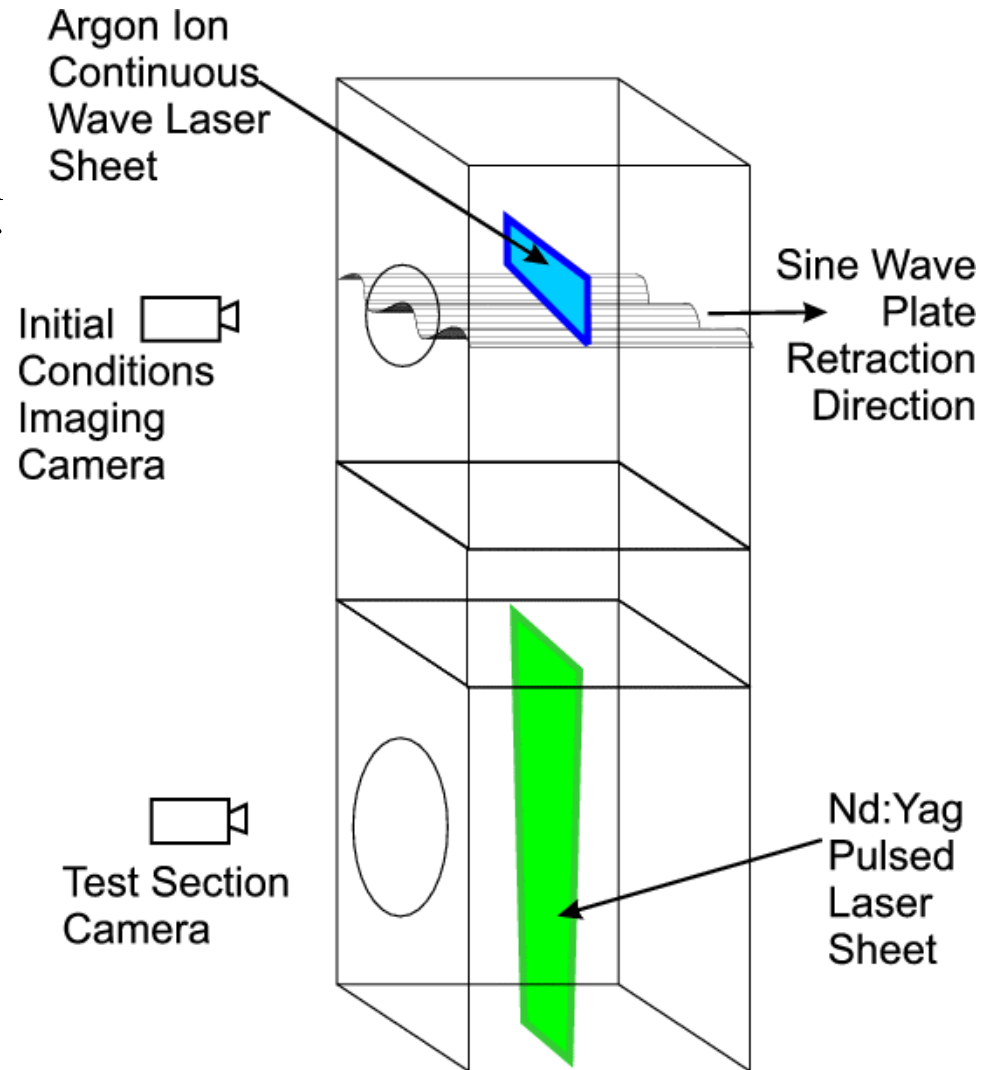
- Comparison with prediction from nonlinear theories shows qualitative agreement
  - - - Sadot *et al.* theory overpredicts at late times
  - · · · Zhang and Sohn theory underpredicts at all times

# Experiment: Combined Imaging Setup

Previously, the RM initial condition was inferred from a reference set of RT experiments.

Dynamic imaging of the interface, prior to being shocked, provides interfacial initial condition data for each RM experiment.

Provides the interface geometry of the initial condition which may be used in a numerical simulation.

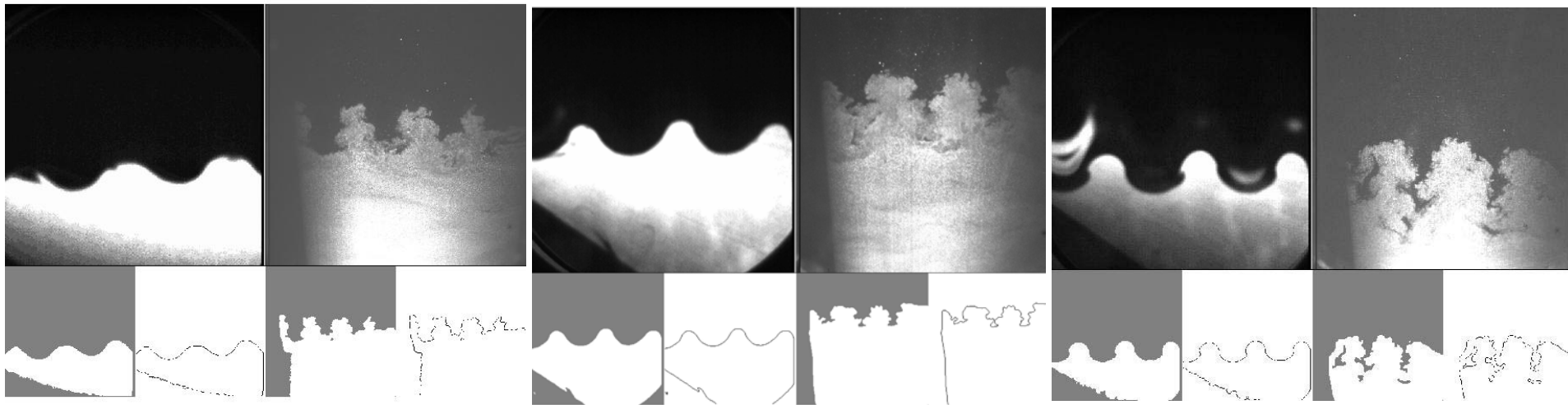


# Experimental conditions

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- Incident shock wave:  $M=2.90$ , in  $\text{CO}_2$
- $P_{\text{initial}} = 1 \text{ atm}$ ,  $T_{\text{initial}} = 300 \text{ K}$
- Post-shock  $A'=0.245$  ( $A=0.206$ ,  $A=(\rho_1-\rho_2)/(\rho_1+\rho_2)$ )
- Planar Mie scattering visualization, smoke particles
- Two-stage retraction ( $\tau_1 \sim 250 \text{ ms}$ ,  $\tau_2 \sim 80 \text{ ms}$ )
- Interface section
  - Ar+ laser @  $\lambda=488 \text{ nm}$ , continuous wave
  - CCD camera,  $256 \times 256$  pixel array, 8 bit/pixel, framing @ 100 fps
- Test section
  - Nd:YAG laser @  $\lambda=532 \text{ nm}$ , 10 ns pulse
  - CCD camera:  $1024 \times 1024$  pixel array, 16 bit/pixel, one shocked image per experiment

# Experiment: CO<sub>2</sub>-air $M=2.90$



Experiment 322

$$x = 0.457 \text{ m}$$

$$\eta_{IC} = 4.64 \text{ mm}$$

$$\eta_{RM} = 13.83 \text{ mm}$$

$$\tau_{RM} = 0.70 \text{ ms}$$

Experiment 351

$$x = 0.756 \text{ m}$$

$$\eta_{IC} = 5.90 \text{ mm}$$

$$\eta_{RM} = 12.3 \text{ mm}$$

$$\tau_{RM} = 1.13 \text{ ms}$$

Experiment 363

$$x = 0.987 \text{ m}$$

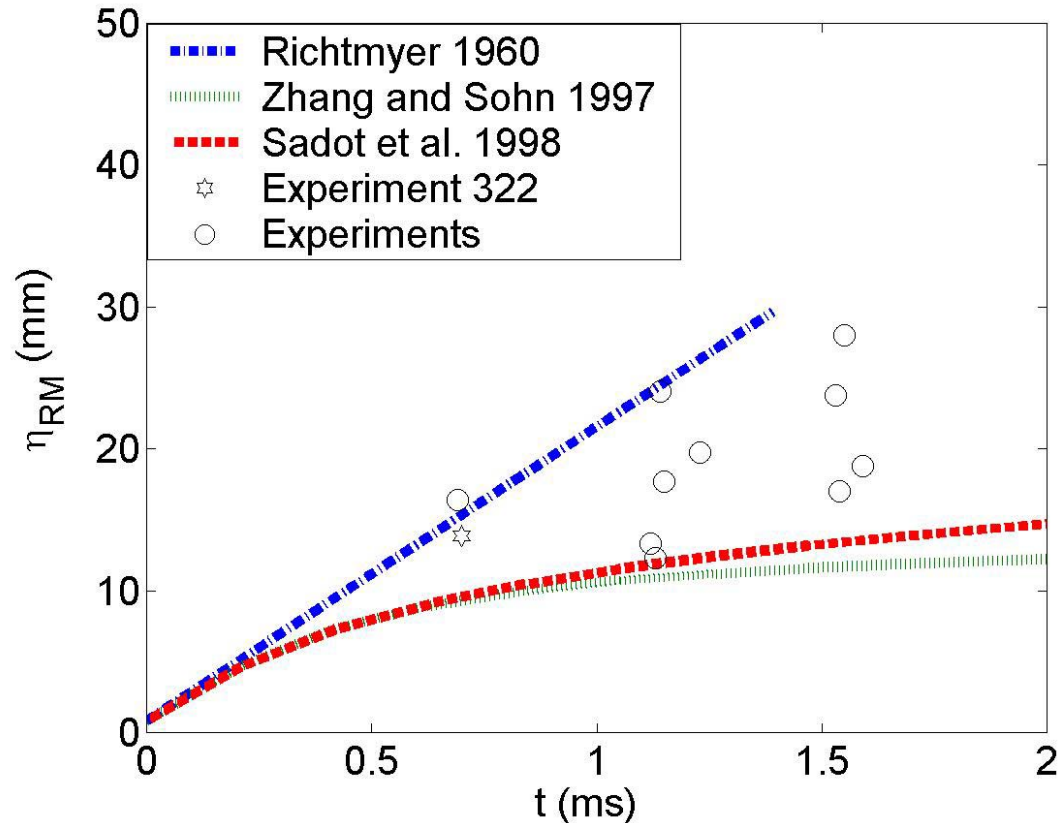
$$\eta_{IC} = 7.81 \text{ mm}$$

$$\eta_{RM} = 28.0 \text{ mm}$$

$$\tau_{RM} = 1.57 \text{ ms}$$

- Initial condition well into nonlinear regime ( $\eta_0/\lambda > 0.2$ )
- Phase inversion of shocked interface

# Comparison with Theories



Comparison with prediction from theories shows qualitative agreement and experimental data bounded by the linear (upper) and nonlinear theories (lower)



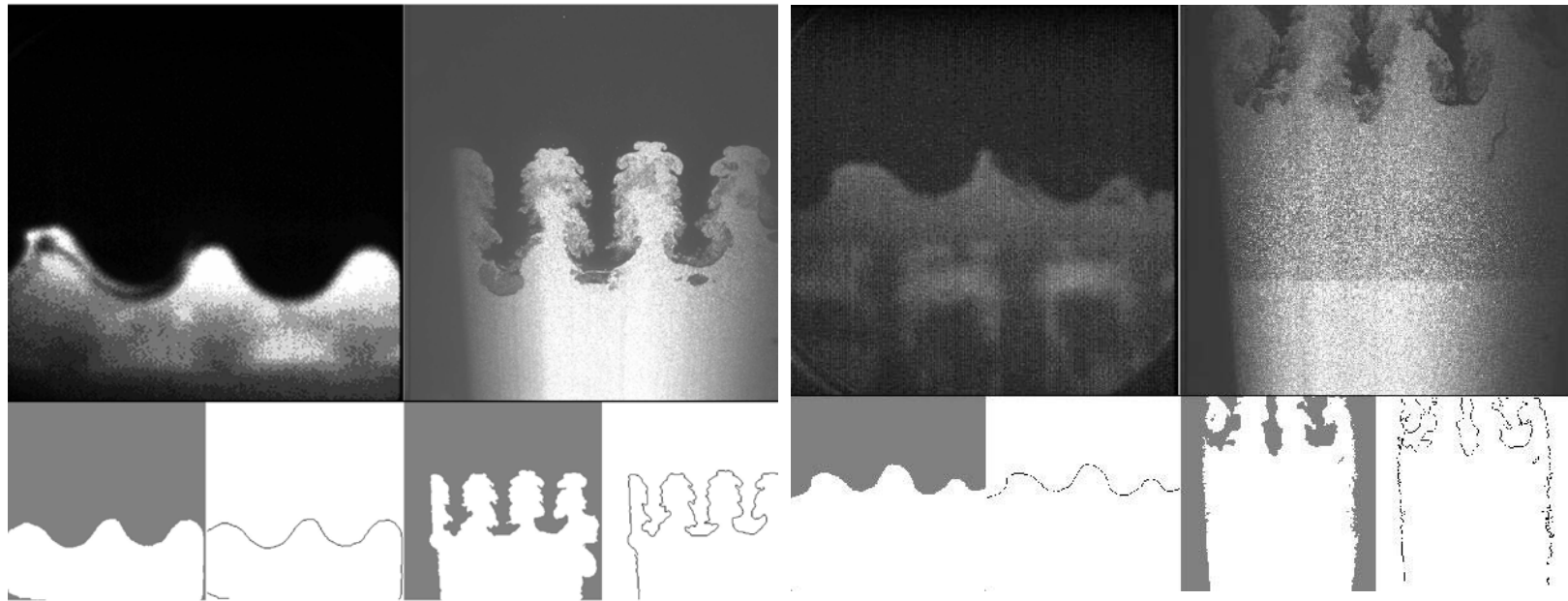
# Conclusions

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- Two dimensional gas-gas interface without a membrane
- Strongly shocked interface (CO<sub>2</sub>-air,  $M$  up to 3.06)
- Initial condition geometry imaged for each experiment
- Scatter in data attributed to extreme sensitivity to initial conditions
- Results are similar to existing linear theories
- Needed improvements
  - Better retraction mechanism for more repeatable initial condition
  - Diagnostic upgrade to obtain more than one shocked image per experiment

# Lower Mach # Experiment: CO<sub>2</sub>-air $M=1.41$

$A=0.2061$ ,  $A'=0.2242$ , Al3003 0.508 mm diaphragm



Experiment 327

$$x = 0.457 \text{ m}$$

$$\eta_{IC} = 6.12 \text{ mm}$$

$$\eta_{RM} = 25.3 \text{ mm}$$

$$\tau_{RM} = 2.60 \text{ ms}$$

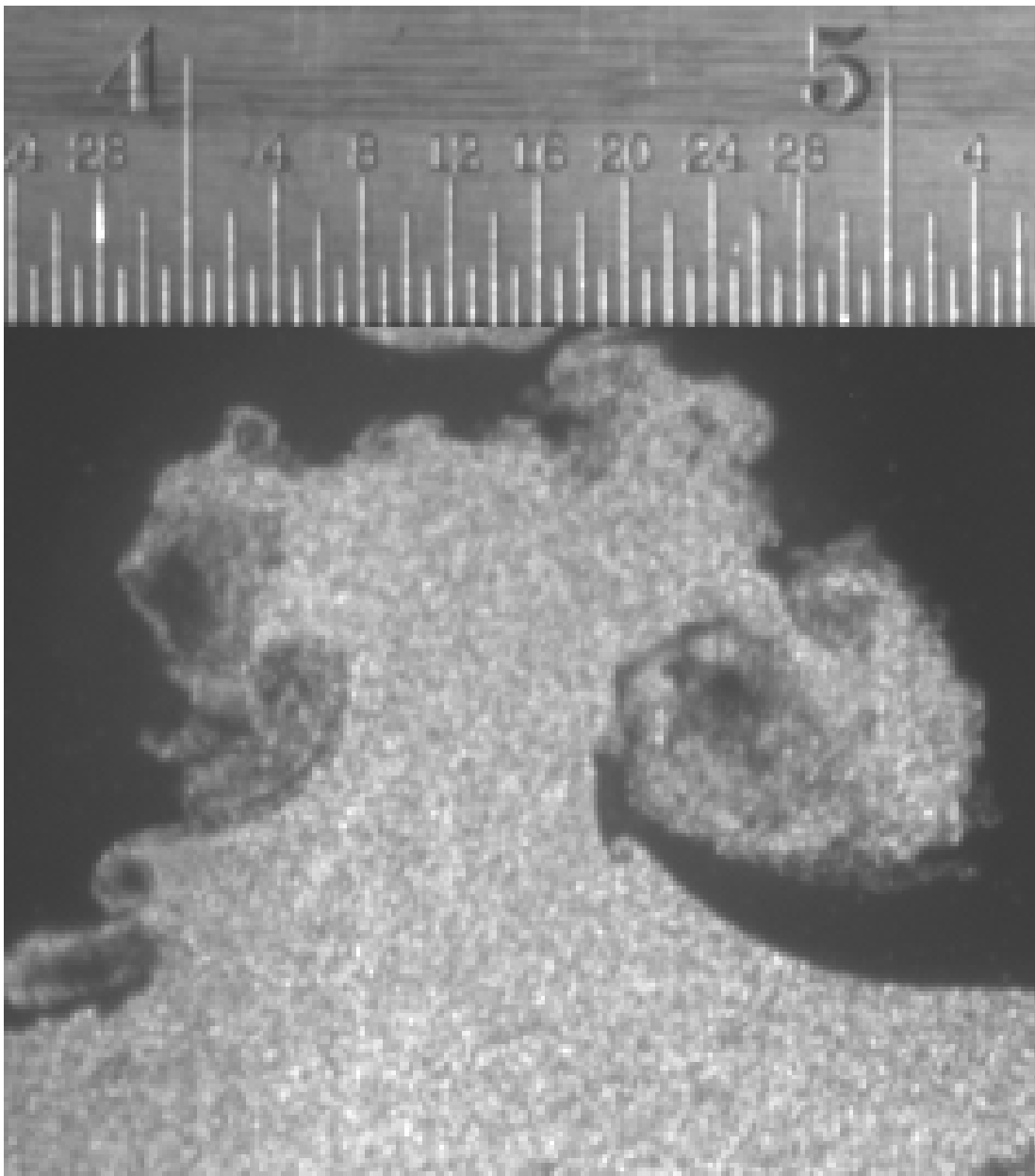
Experiment 343

$$x = 0.756 \text{ m}$$

$$\eta_{IC} = 5.45 \text{ mm}$$

$$\eta_{RM} = 23.0 \text{ mm}$$

$$\tau_{RM} = 3.97 \text{ ms}$$



Magnified image of one peak from test 327, the scale above the instability is in inches.