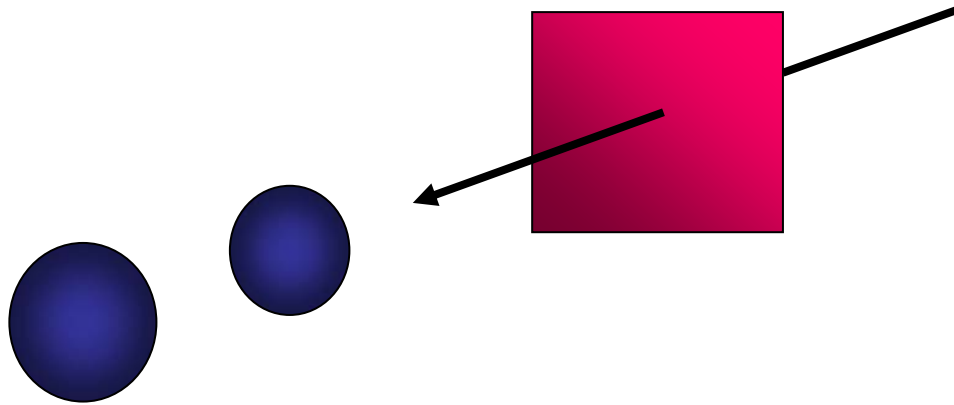


# *The Interaction of two shocked bubbles*



K. Levy<sup>(1,2)</sup>, O. Sadot<sup>(1,2)</sup>, A. Yosef-Hai<sup>(1,2)</sup>,  
G. Ben-Dor<sup>(1)</sup>, D. Shvarts<sup>(1,2)</sup>

1) Ben-Gurion Univeristy, Beer Sheva, Israel

2) Nuclear Research Center Negev, Israel

# Introduction

The aim is to model the passage of a shock wave through an array of bubbles. The first step\* was to find the scaling of the interaction between a single bubble and a shock wave. The second step shown here is the interaction between two shocked bubbles. The main parameters investigated are:

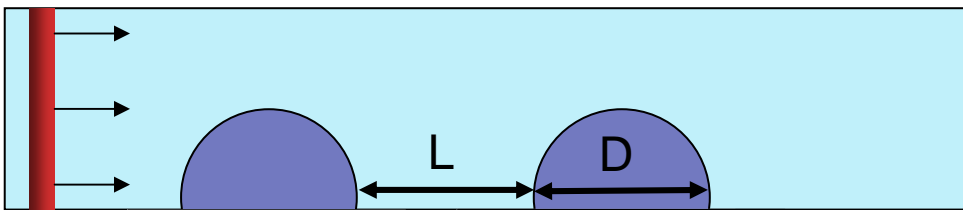
- The nature of the interaction between the bubbles.
- The range of the interaction.
- The mass velocity interaction.
- The effect on the interaction of the Mach number and the bubbles diameter ratio.

\*K. Levy et al., Laser and Particle Beams, (2003) **21**, 335-339

# Computational method

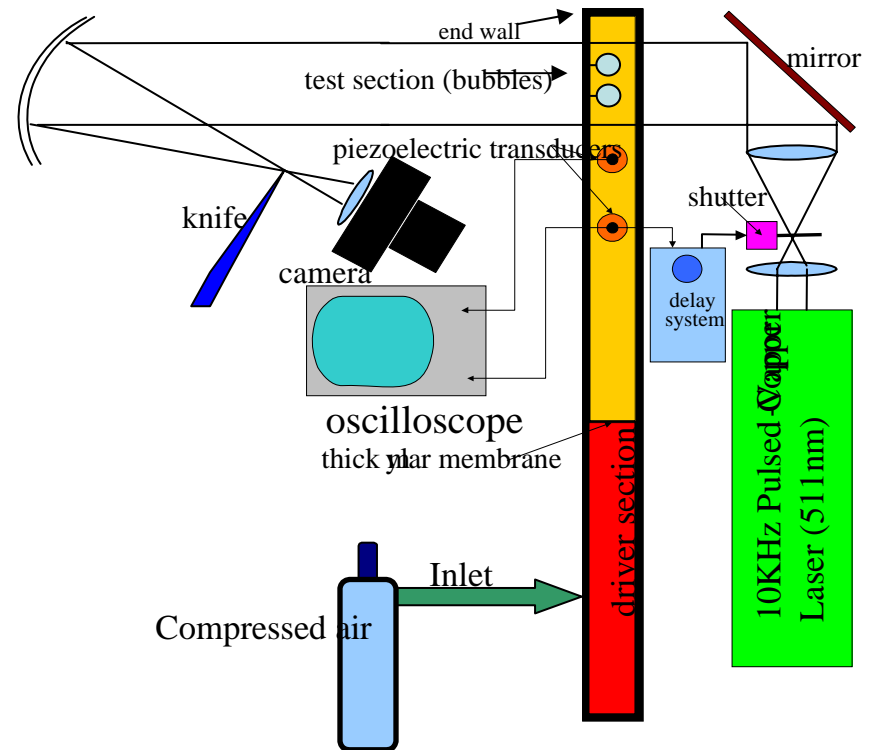
- Leeor-2D\*: ALE, interface-tracking, finite differences

Initial condition



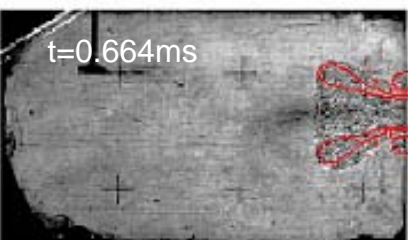
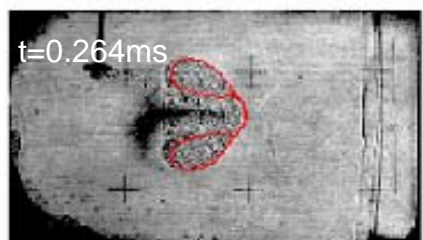
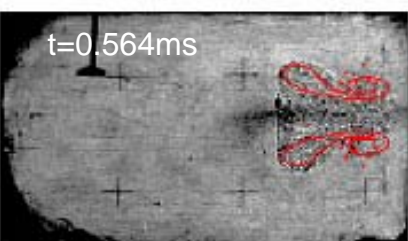
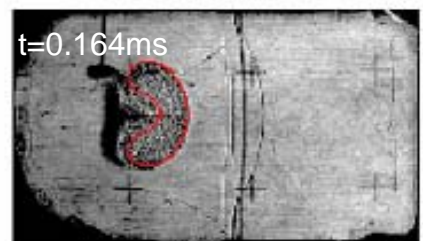
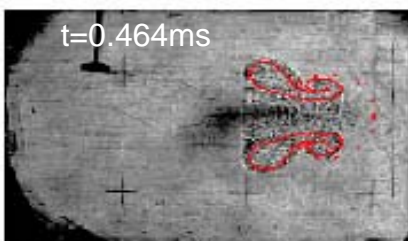
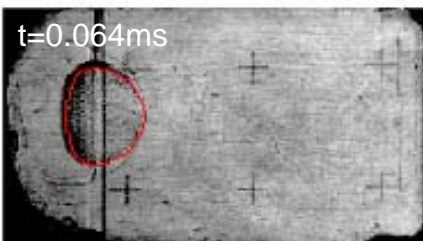
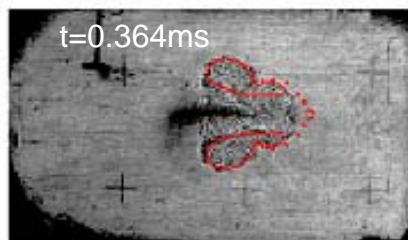
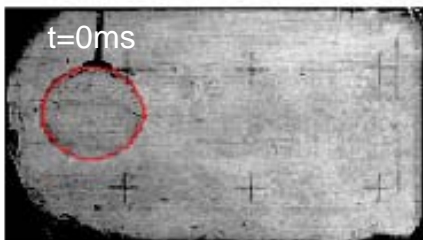
- ambient gas - air
- heavy bubble (fast/slow) – SF<sub>6</sub>,  
density ratio  $\eta=5.034$ ,  $r_0=1cm$
- light bubble (slow/fast) – He,  
density ratio  $\eta=0.138$ ,  $r_0=1cm$
- mach range - 1.05 to 4
- boundary conditions - free slip
- shock tube half width - 4 cm

# Experimental Apparatus



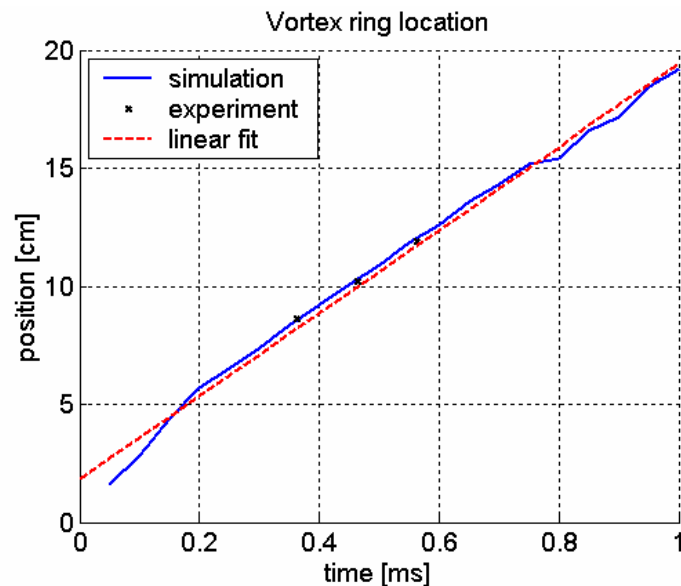
\*D. Shvarts et al., Phys. Plasma **2**, 2465 (1995)  
Cambridge, UK

# Single bubble slow/fast (air-helium), $M=1.22$



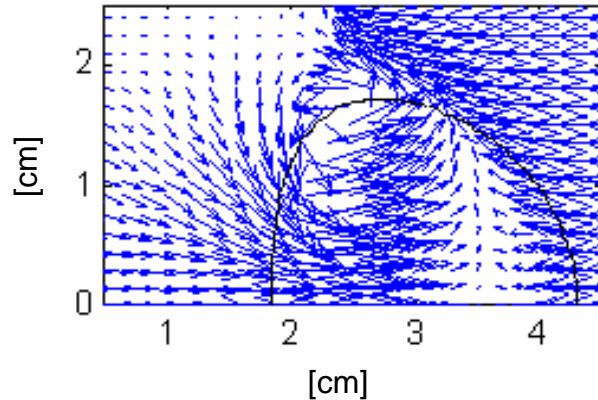
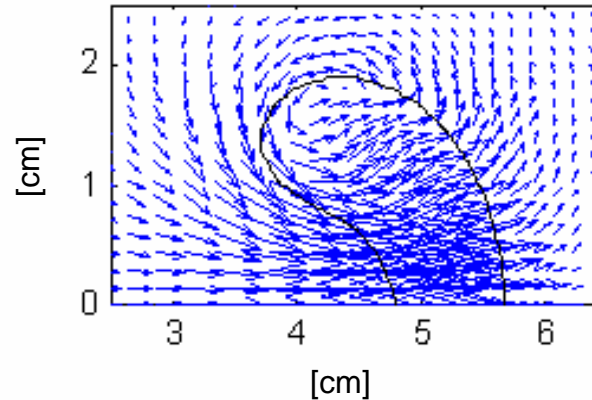
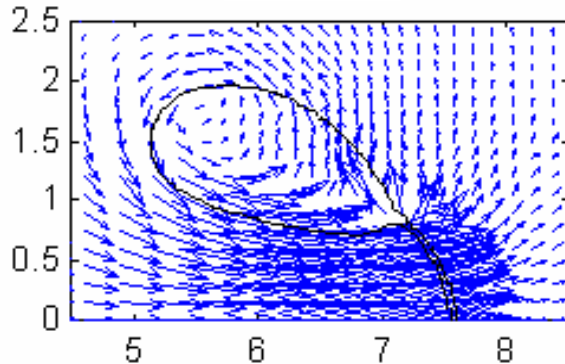
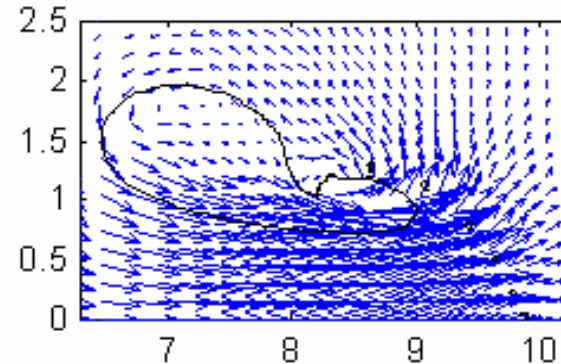
- Schlieren images of the experiment
- **Red contour:** gas interface from the simulation
- Good agreement is found during the early and late times of the interaction.

## Simulation/experiment comparison



# Vortex ring formation - velocity field

## low/fast, $M=1.22$

(a)  $t=0.064\text{ms}$ (b)  $T=0.164\text{ms}$ (c)  $t=0.264\text{ms}$ (d)  $t=0.364\text{ms}$ 

The velocity field is drawn in a coordinate system moving with the shocked air

(a) Acceleration of the upstream interface. Rotational flow is created.

(b) Ambient gas is drawn into a low pressure area in the center of the bubble.

(c) The upstream and downstream interfaces meet, the bubble transforms into a torus-like shape.

(d) The vortex ring is formed.





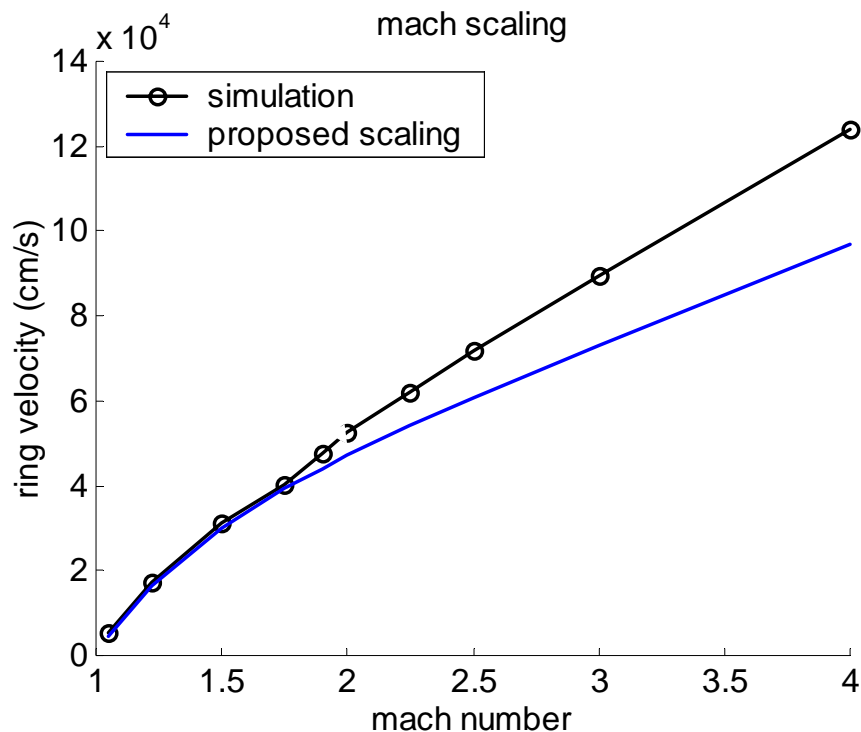
# Scaling in the shock bubble interaction

## Dimensional analysis

Velocity normalization:

$$U_i = g_i \cdot \frac{\Gamma}{R} = g_i \cdot f(M, \eta, \gamma) \cdot c_s$$

$i$  - ring, jet, etc...



$g_i$  - is a constant representing the influence of the topology of the problem, the boundary conditions and the specific velocity  $U_i$ .

$R$  - initial bubble radius

$M$  - Mach number

$\Gamma$  - circulation

$\eta$  - density ratio

$\gamma$  - specific heat ratio

$c_s$  - speed of sound

Samtaney & Zabusky, JFM. **269** (1994)

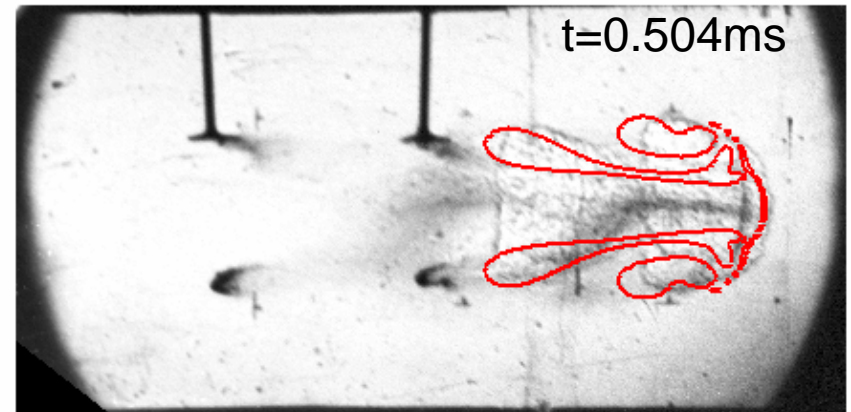
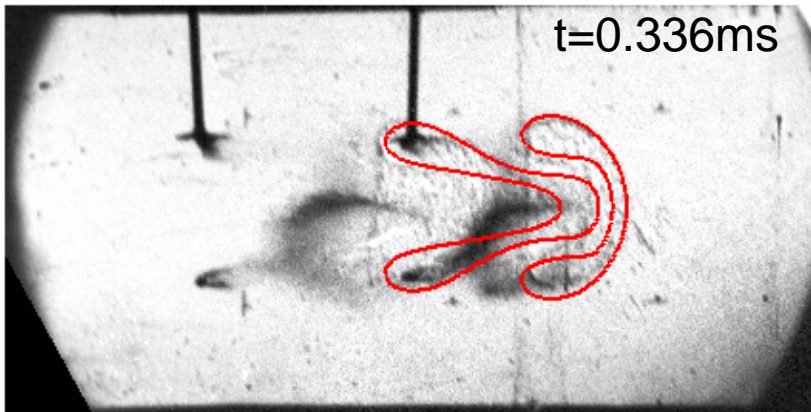
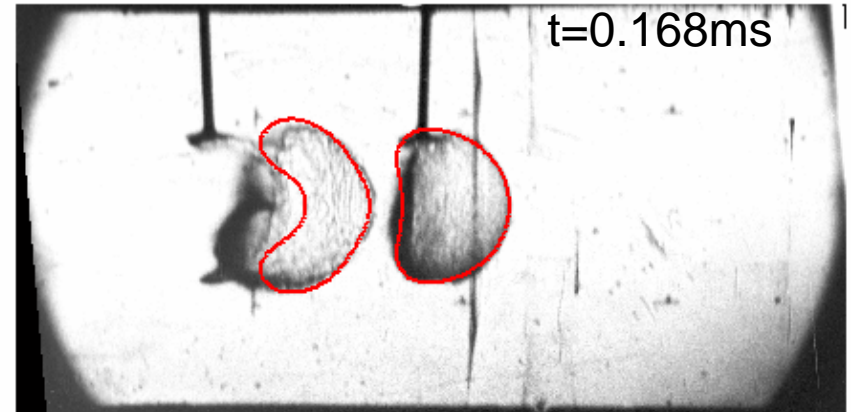
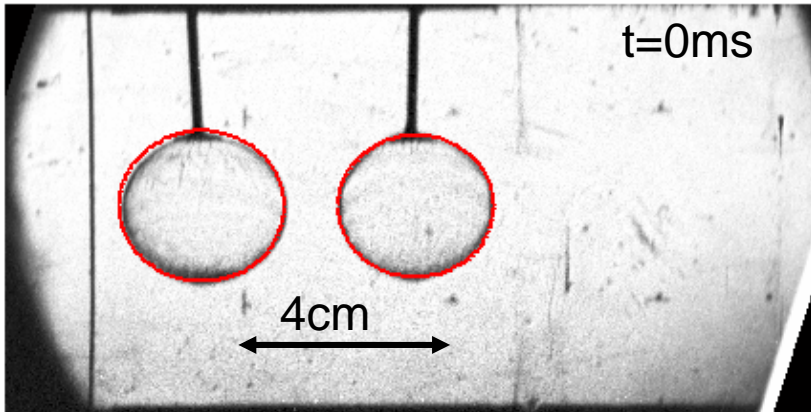
$$\Gamma = \left(1 + \frac{\pi}{2}\right) \cdot \frac{2\gamma^{1/2}}{1+\gamma} (1 - \eta^{-1/2}) \left(1 + \frac{1}{M} + \frac{2}{M^2}\right) (M - 1) \cdot R \cdot c_s$$



- Good agreement is found for  $M < 2$ .

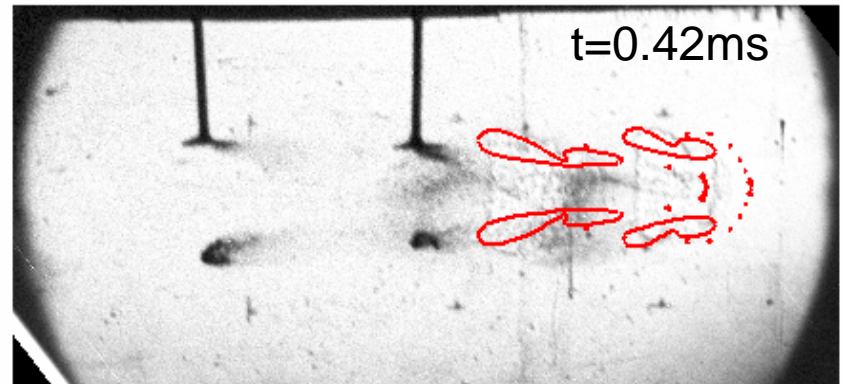
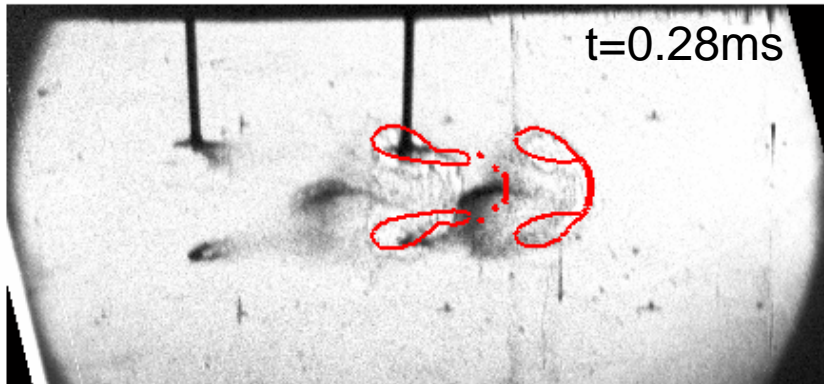
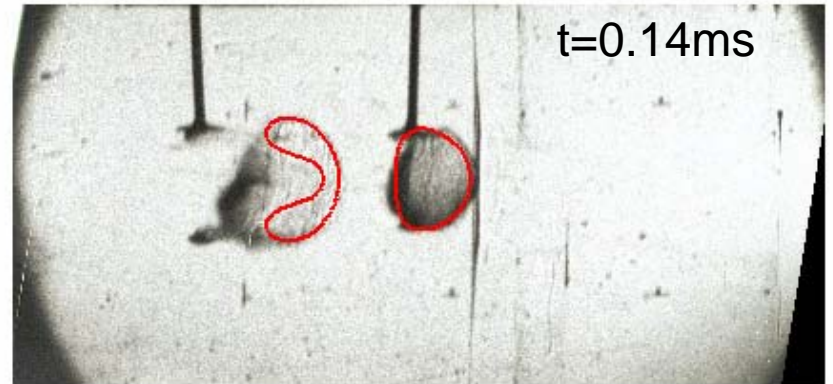
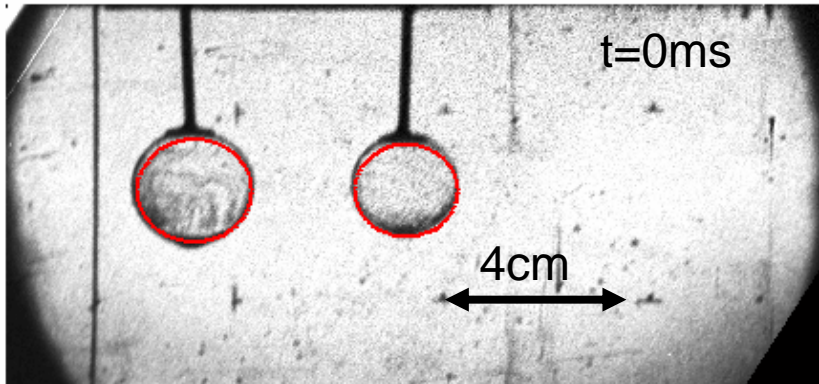
# Two bubbles, $L/D=1/3$ , ( $D=3\text{cm}$ )

slow/fast (air-helium), mach=1.22



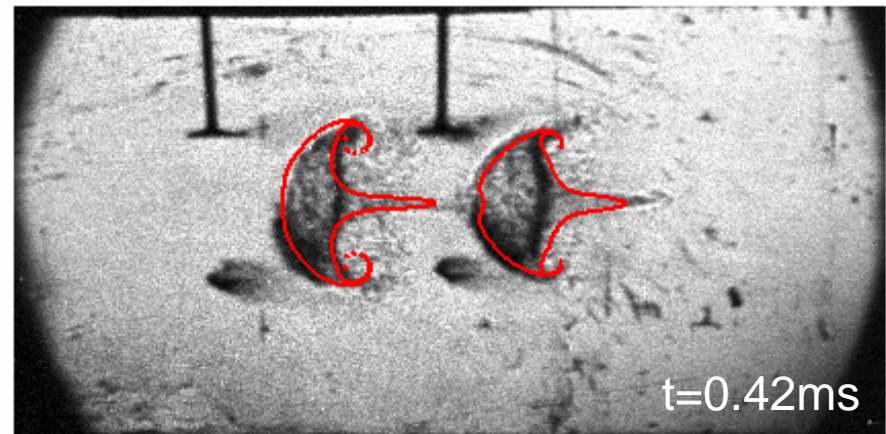
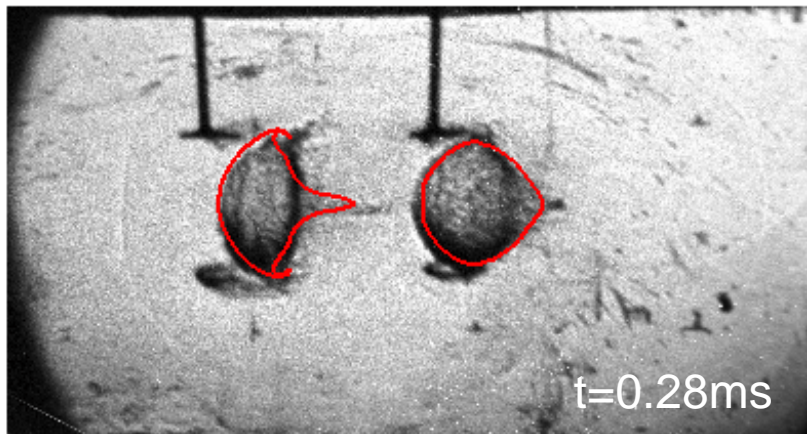
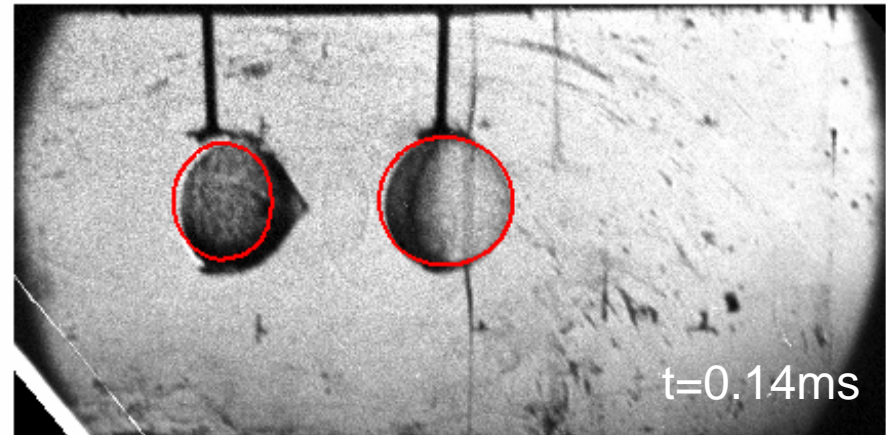
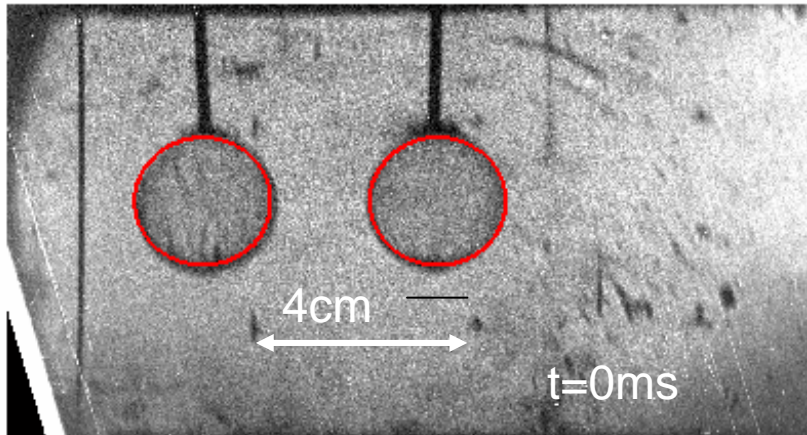
# Two bubbles, $L/D=1$ , ( $D=2\text{cm}$ )

slow/fast (air-helium), mach=1.22

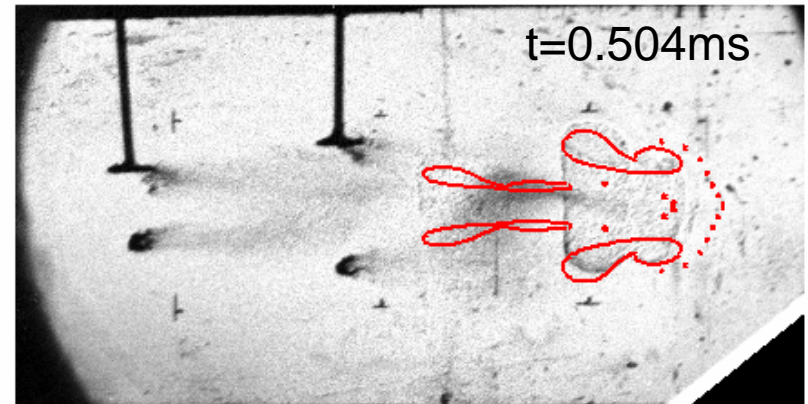
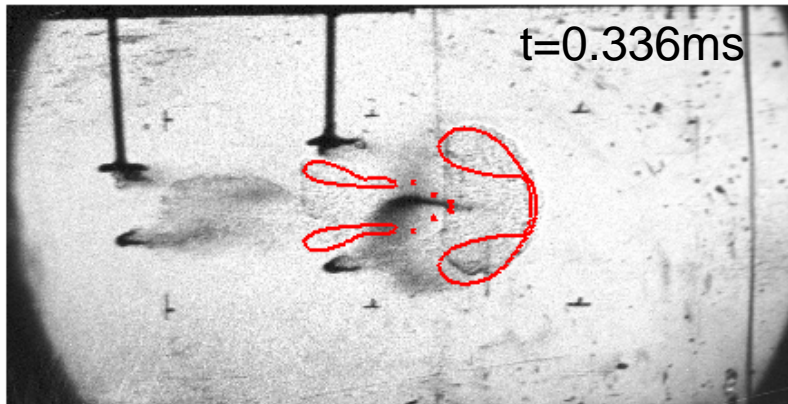
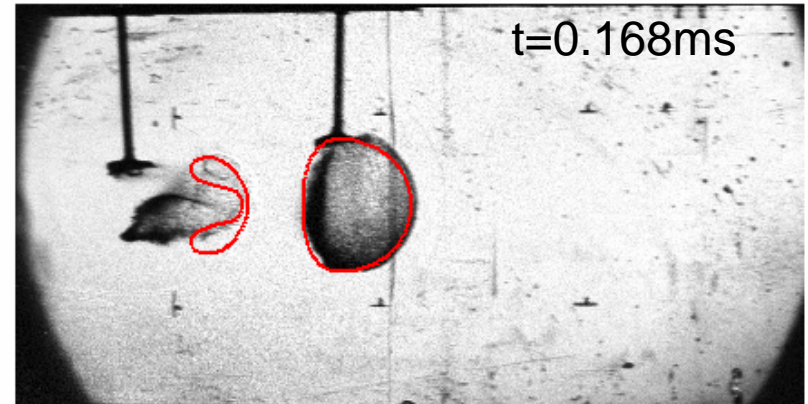
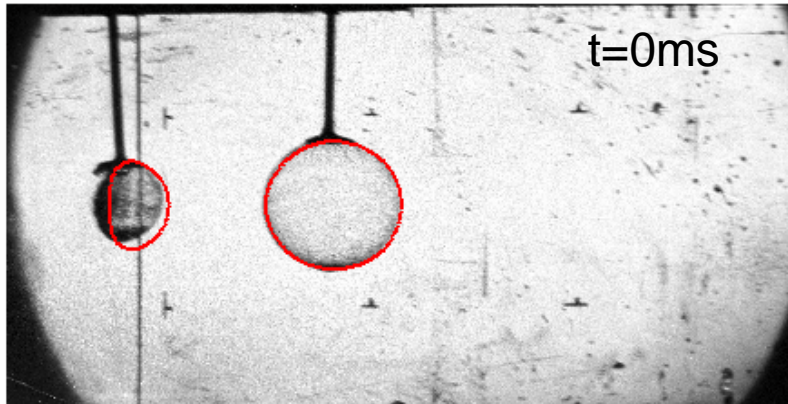


# Two bubbles, $L/D=2/3$ , ( $D=3\text{cm}$ )

fast/slow (air-SF<sub>6</sub>), mach=1.22

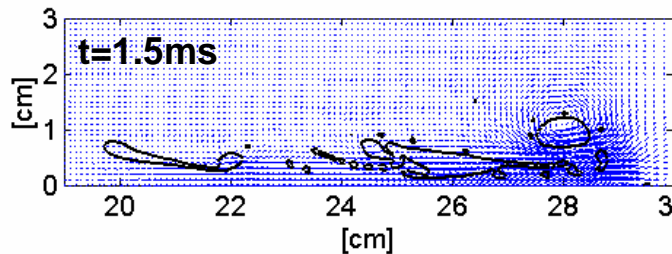
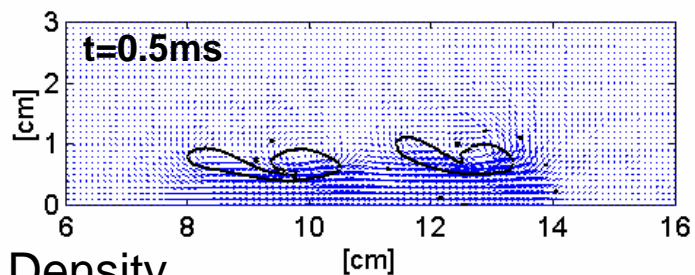
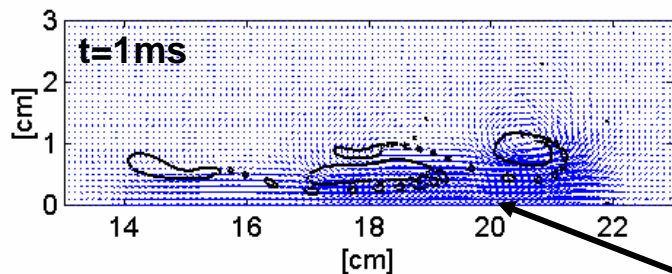
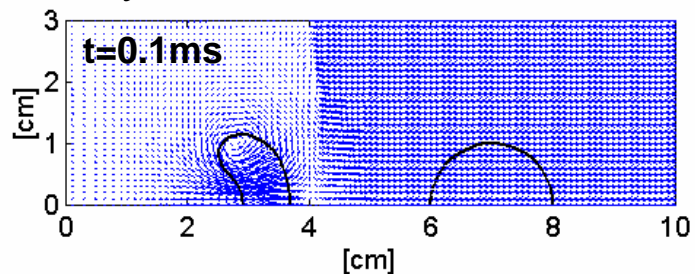


# Two bubbles, ratio 1.6, $L/D=0.75$ , ( $D=2.6\text{cm}$ ) *slow/fast (air-helium), mach=1.22*



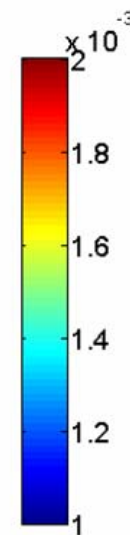
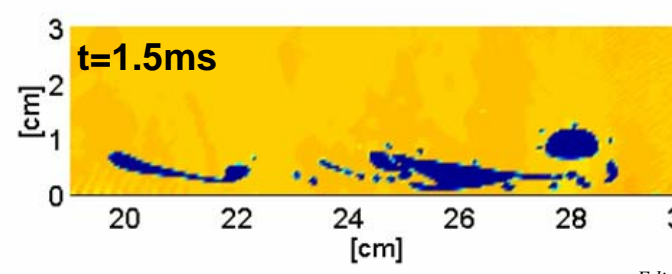
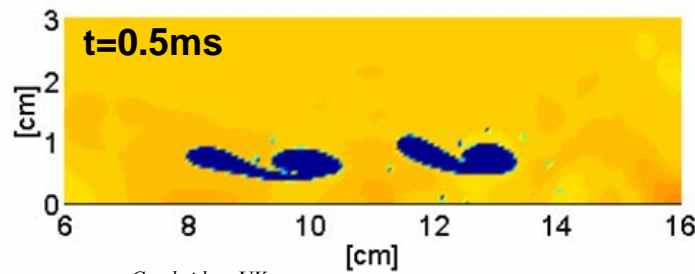
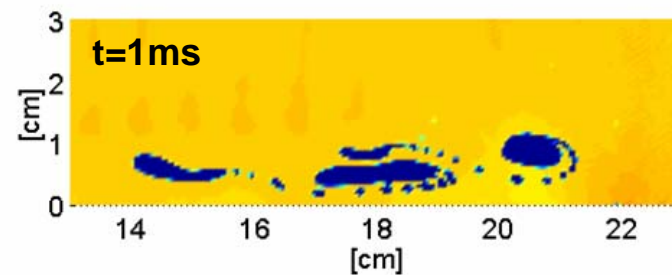
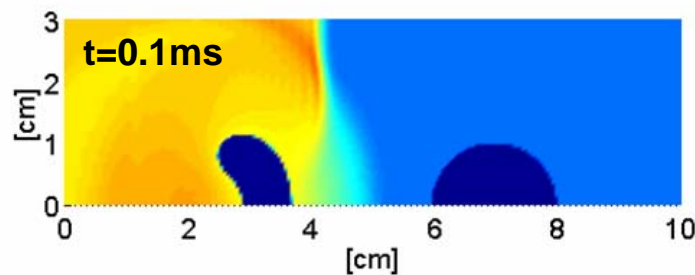
# Typical Simulation - $L/D=1.5$ ( $D=2\text{cm}$ )

Velocity field



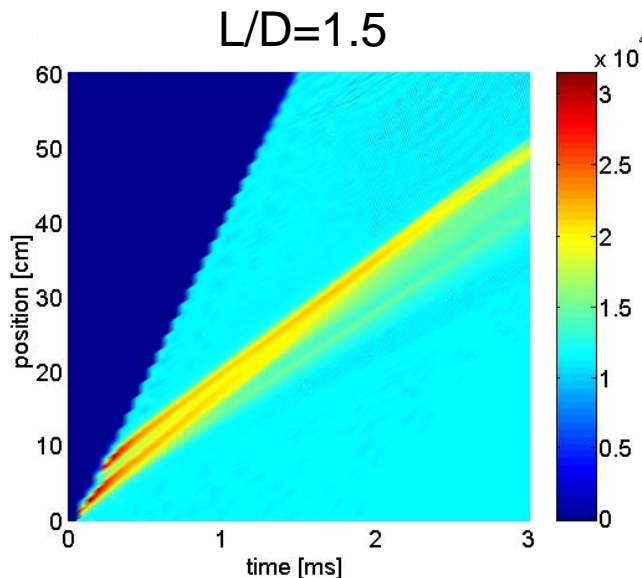
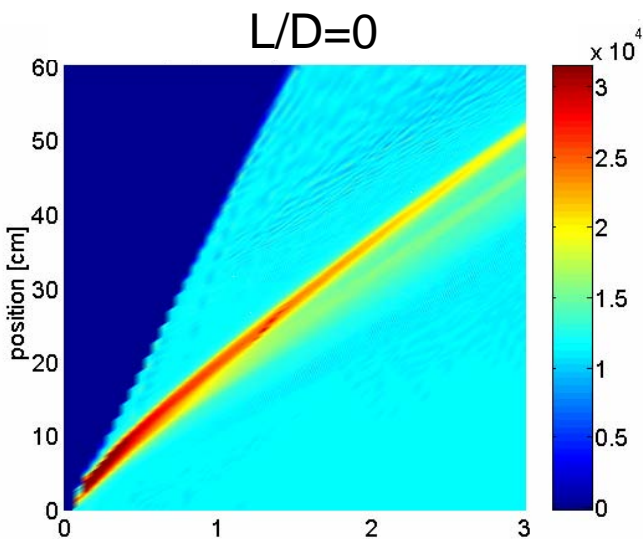
- deformation of upstream vortex ring
- Suction of upstream vortex into the downstream vortex

Density



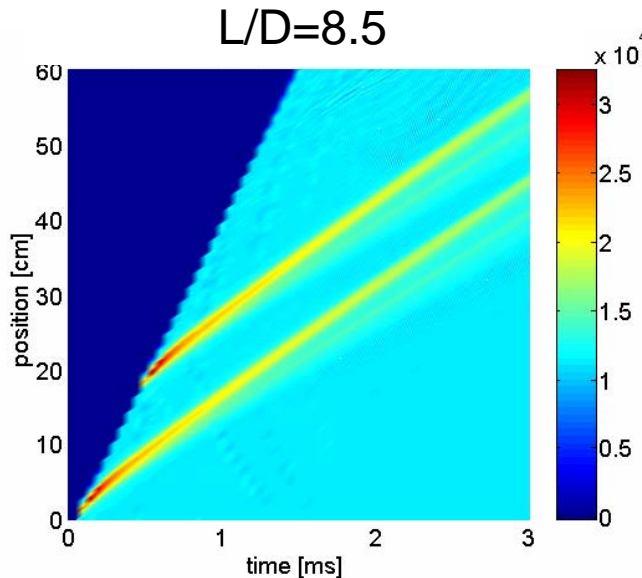
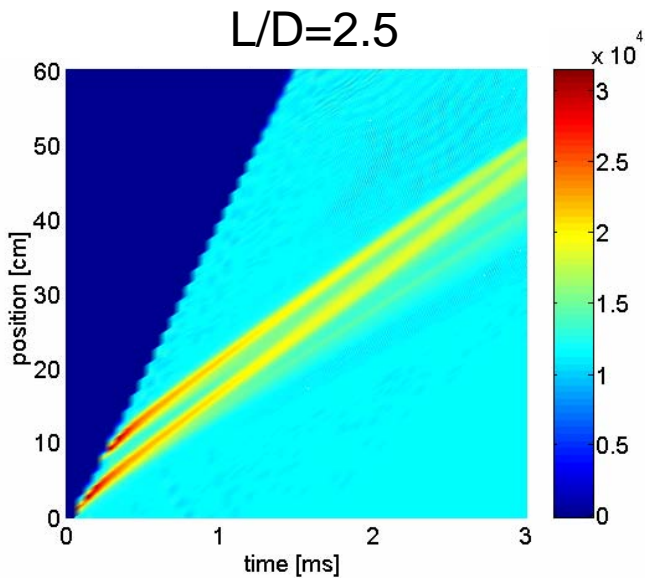
# Symmetry axis velocity profile

**Early interaction:**  
No period of two co-existing vortex rings



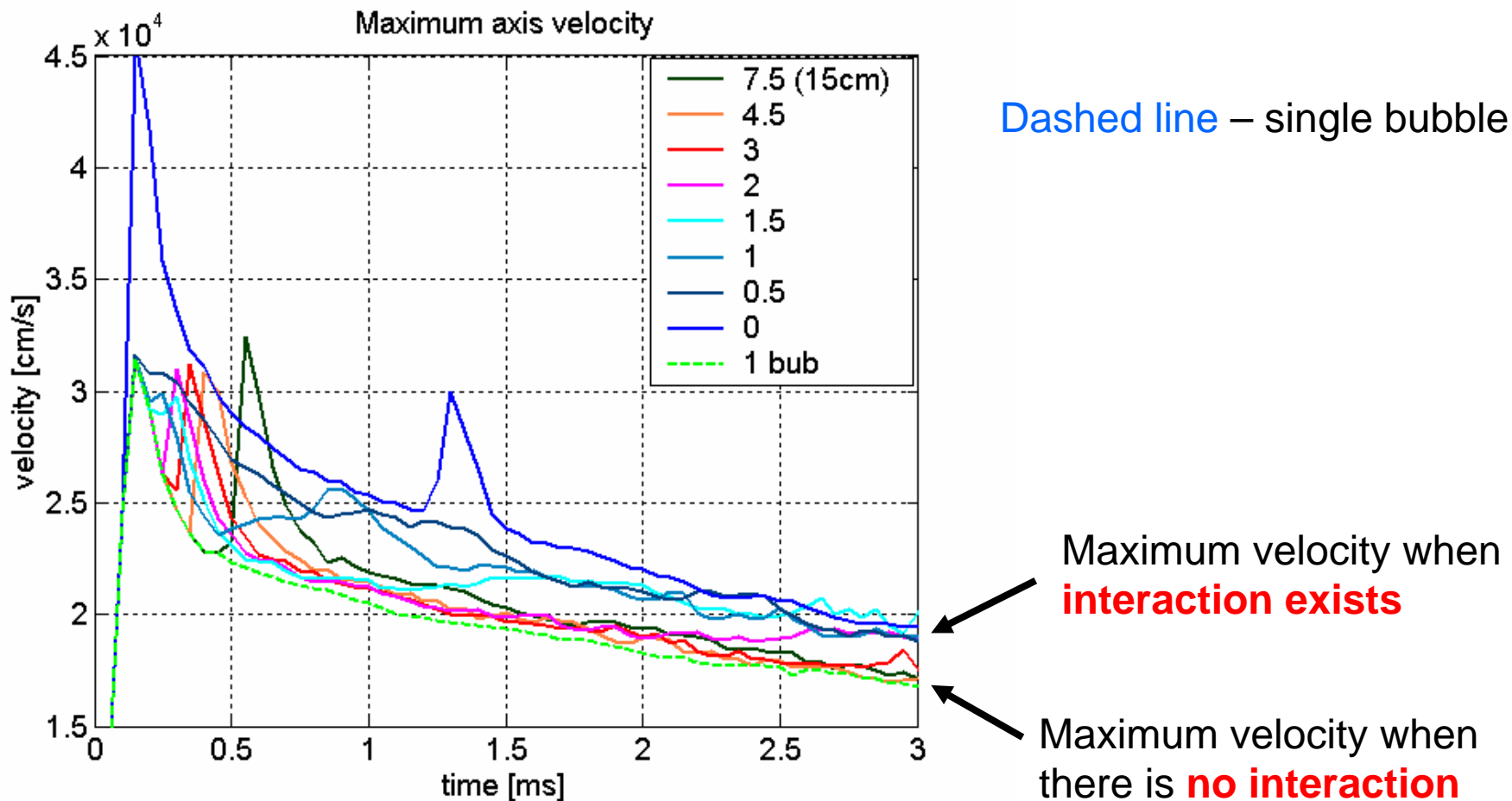
**Moderate interaction**  
The vortex ring interact shortly after formation

**Late interaction**  
Vortex rings flow interdependently for a significant period



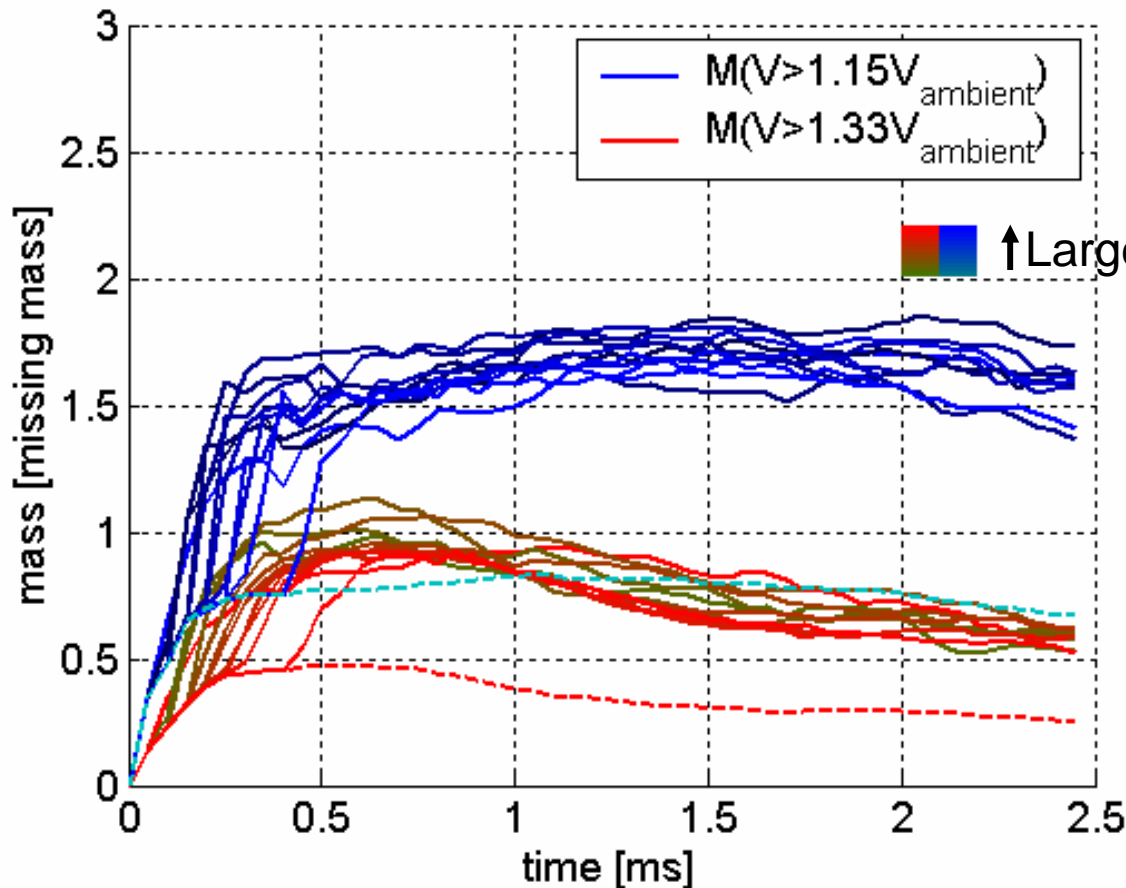
**No interaction**  
according to prediction based on the vortex ring velocity

# Maximum velocity on axis



- There are two asymptotic velocities => indication on occurrence of interaction
- 1cm difference in initial separation leads to 1ms time delay in the start of the interaction

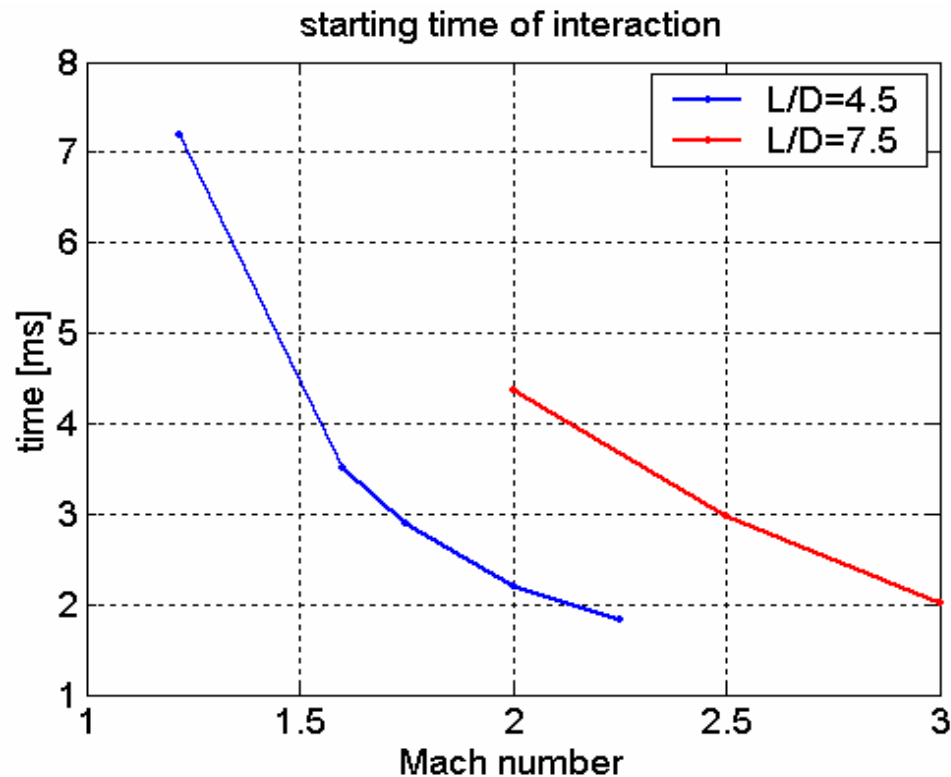
# Mass velocity criterion



Mass velocity criterion:  
summation of the mass with velocity  
higher than a certain value

- dashed line – single bubble
- Two bubbles donate twice the mass of one bubble.
- **The mass-velocity criterion is insensitive to interaction between the vortex rings.**

# Interaction time, Mach number

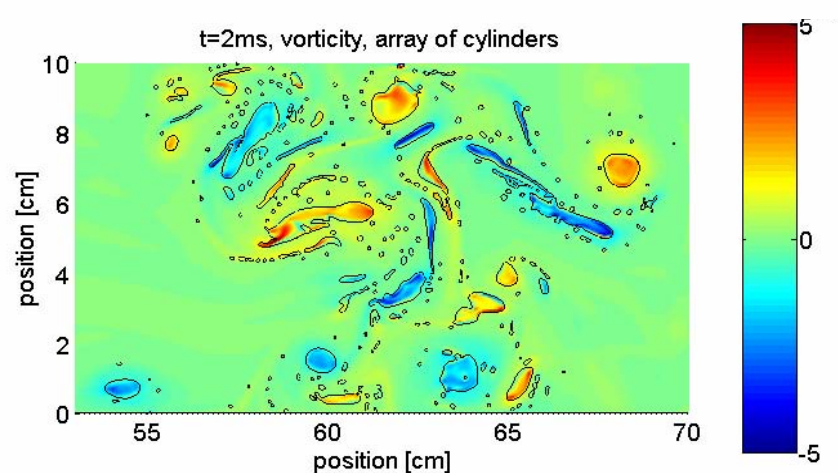
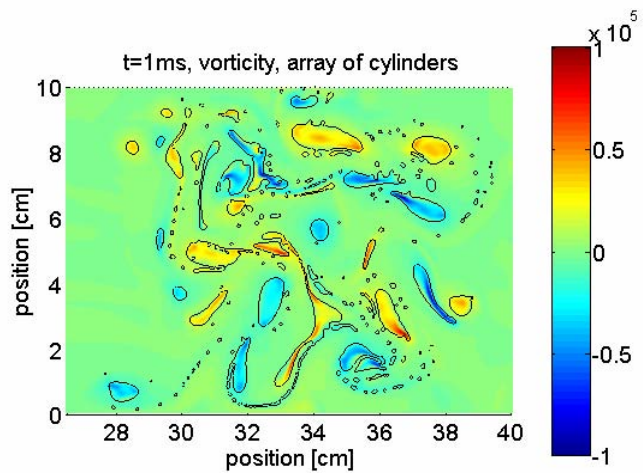
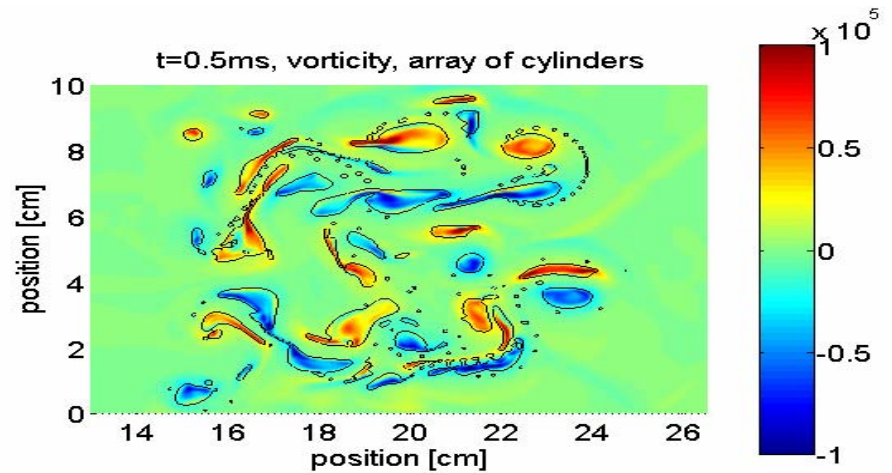
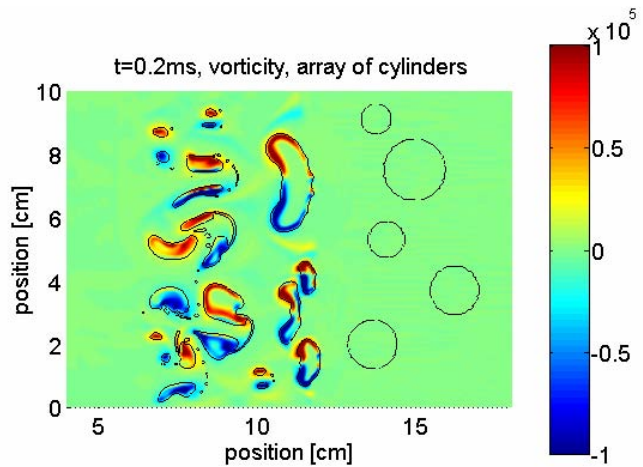
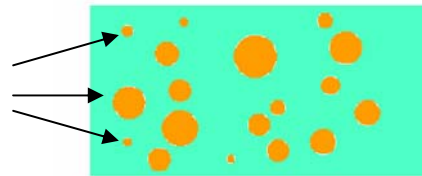


- Higher Mach number => the interaction occurs earlier
- L/D=4.5: Mach higher than 2.5 – merger before formation of second vortex ring.

# Random array of cylindrical bubbles

Vorticity

Randomly distributed cylinders



# Summary

- There are two types of interaction:
  1. merger of bubbles immediately after formation
  2. swirling of the upstream vortex into the center of the downstream vortex.
- There is a distance after which there is no interaction.
- The maximum of the horizontal velocity on the symmetry axis is an indicator as to whether there is interaction between two bubbles.
- The mass velocity criterion is insensitive to the occurrence of the interaction.