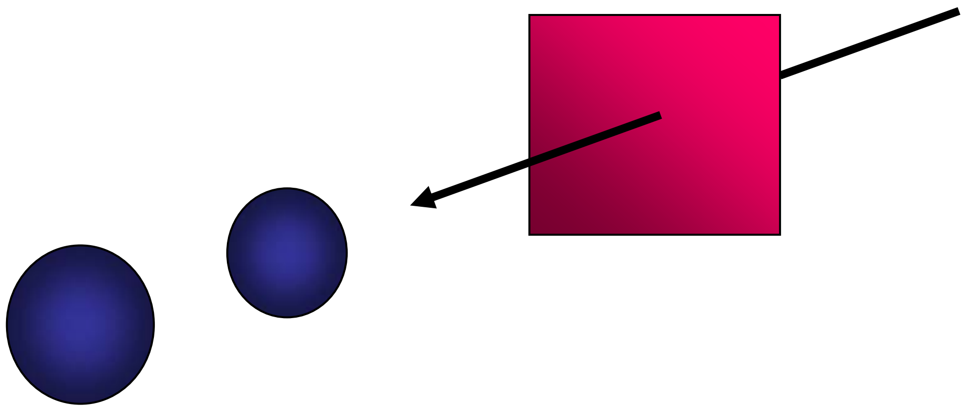
The Interaction of two shocked bubbles



K. Levy[1,2], O. Sadot[1,2], A. Yosef-Hai[1,2], G. Ben-Dor[1], D. Shvarts[1,2]

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:

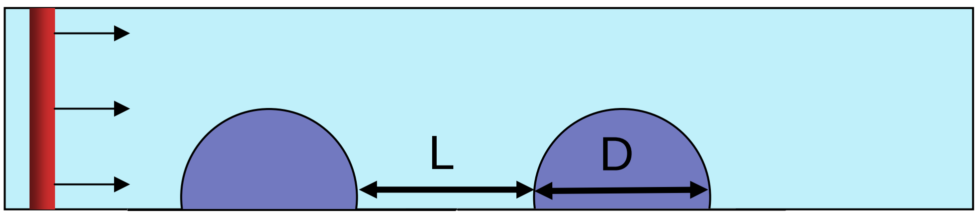
- The nature of the interaction between the bubbles.
- The range of the interaction.
- The mass velocity interaction.
- The effect on the interaction of the Mach number and the bubbles diameter ratio.

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

Computational method

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

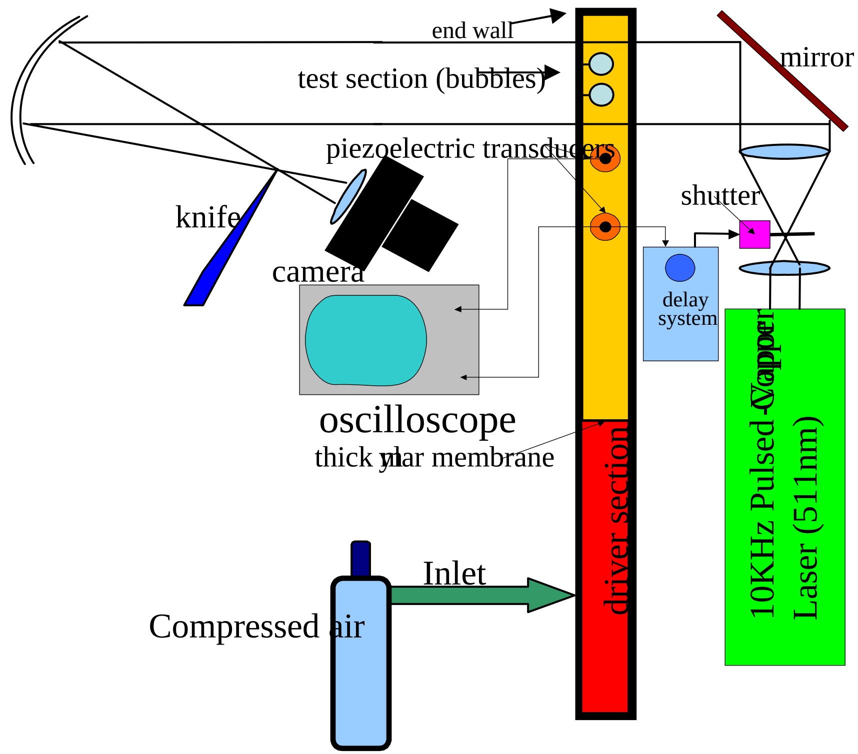
Initial condition



- ambient gas - air
- heavy bubble (fast/slow) – SF_6,
  density ratio η=5.034, r_0=1cm
- light bubble (slow/fast) – He,
  density ratio η=0.138, r_0=1cm
- mach range - 1.05 to 4
- boundary conditions - free slip
- shock tube half width - 4 cm

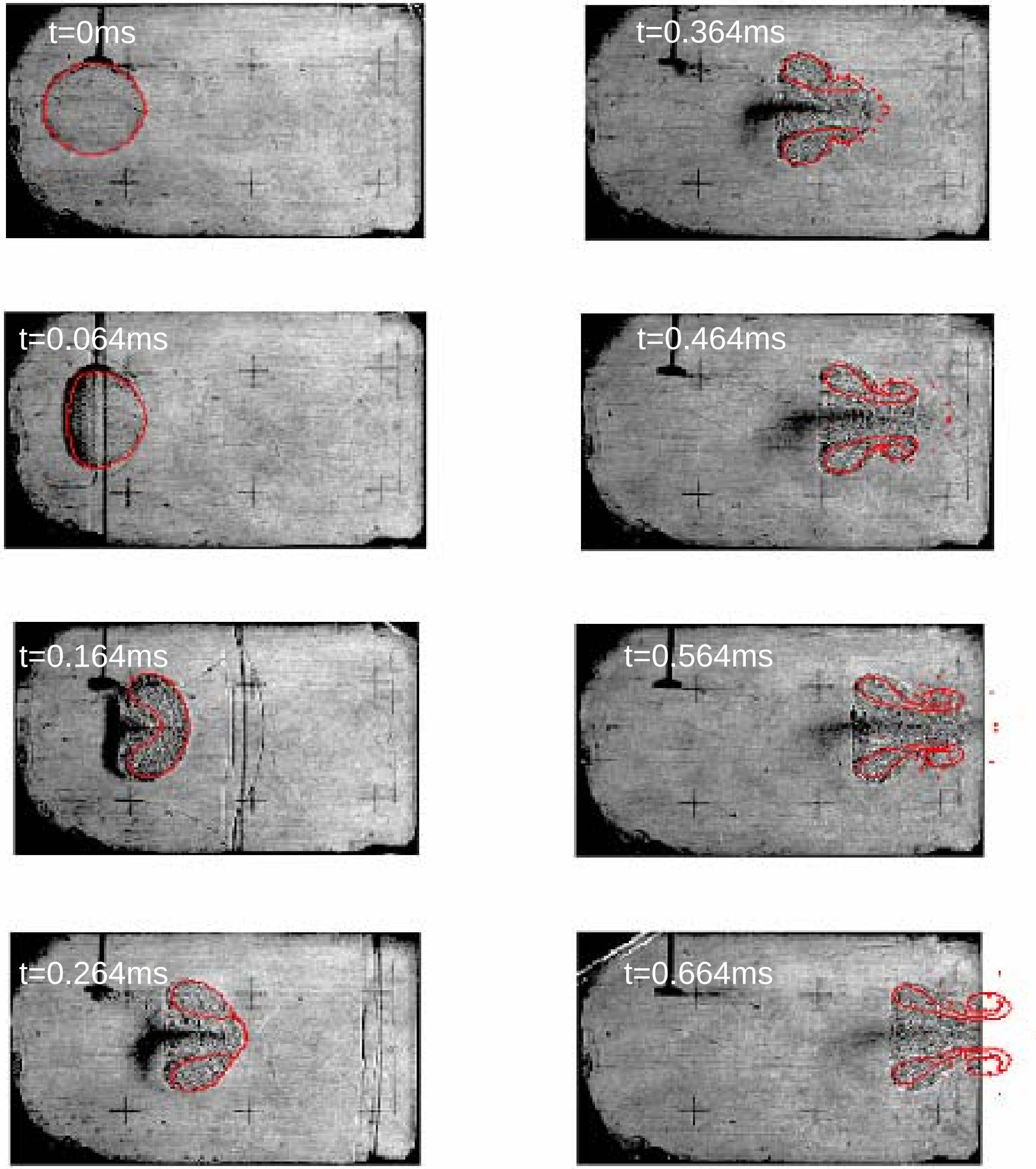
*D. Shvarts et al., Phys. Plasma **2**, 2465 (1995)

Experimental Apparatus



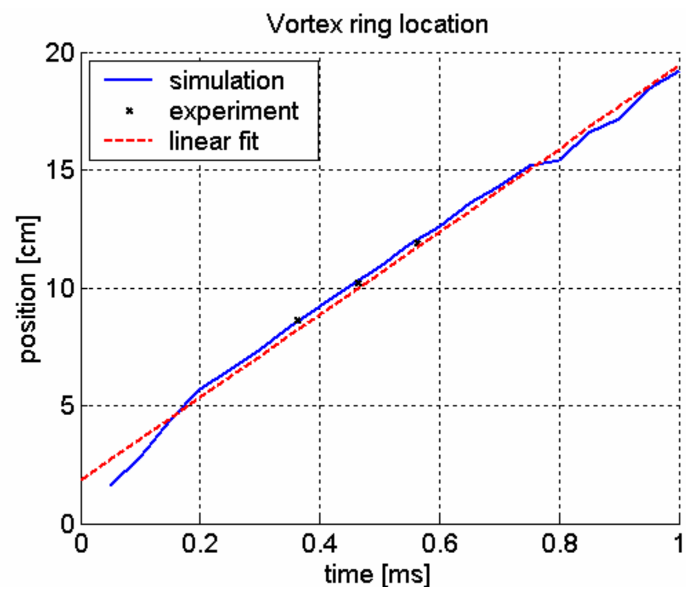
Single bubble

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



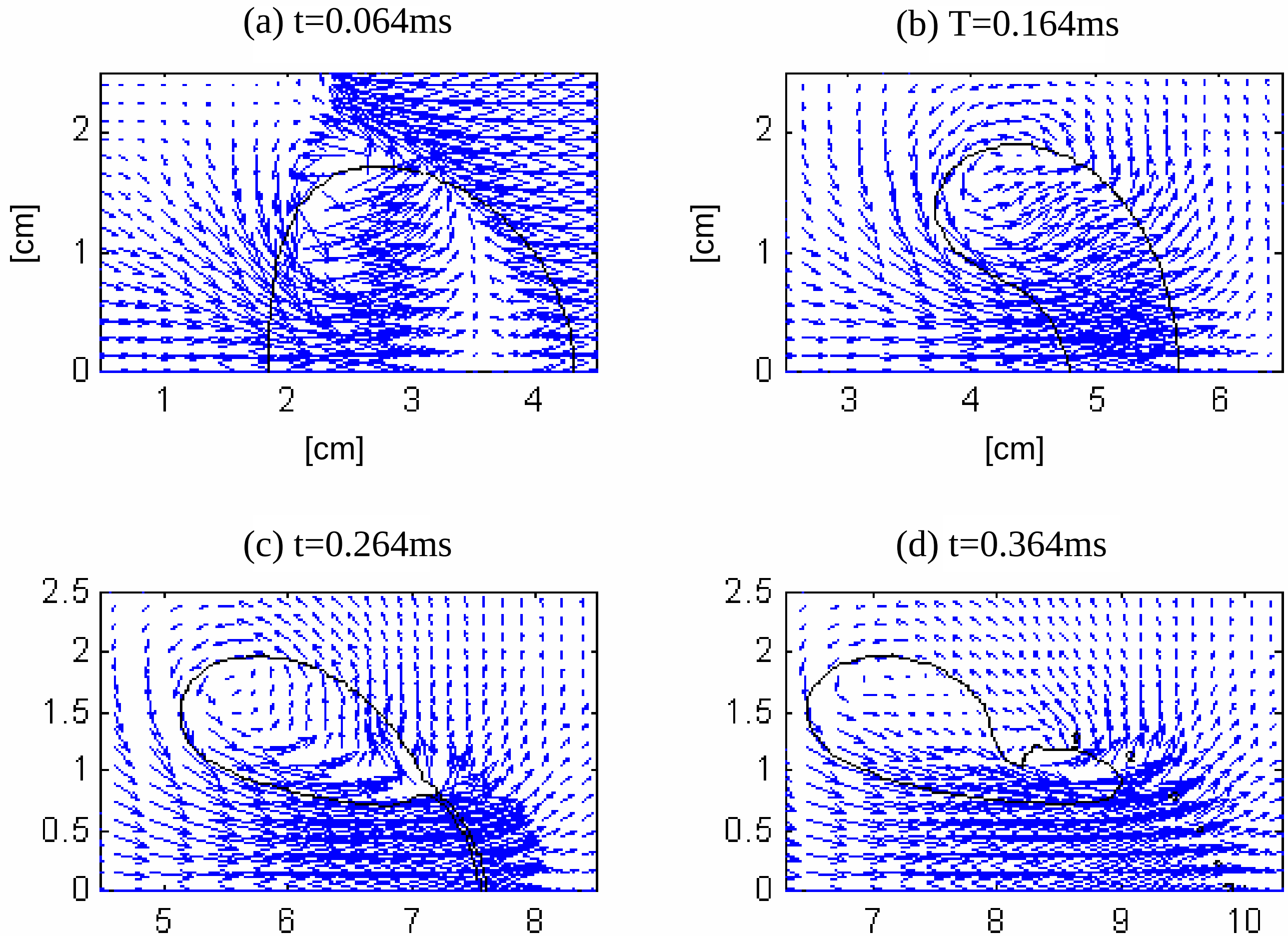
- Schliren images of the experiment
- Red contour: gas interface from the simulation
- Good agreement is found during the early and late times of the interaction.

Simulation/experiment comparison



Vortex ring formation - velocity field

low/fast, M=1.22



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

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

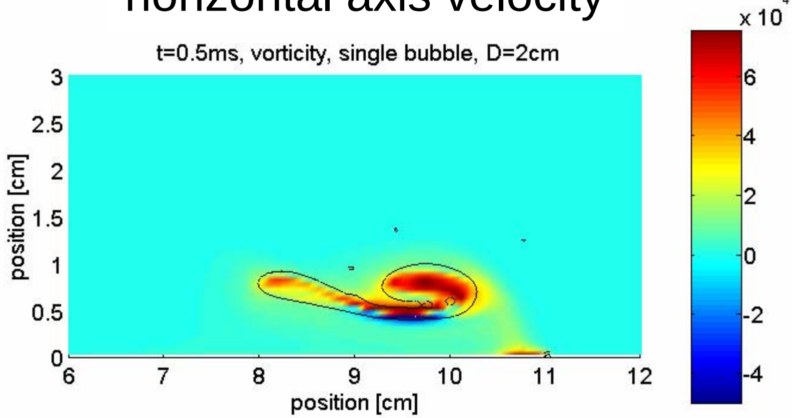
(b) Ambient gas is drawn into a low pressure area in the center of the bubble.

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

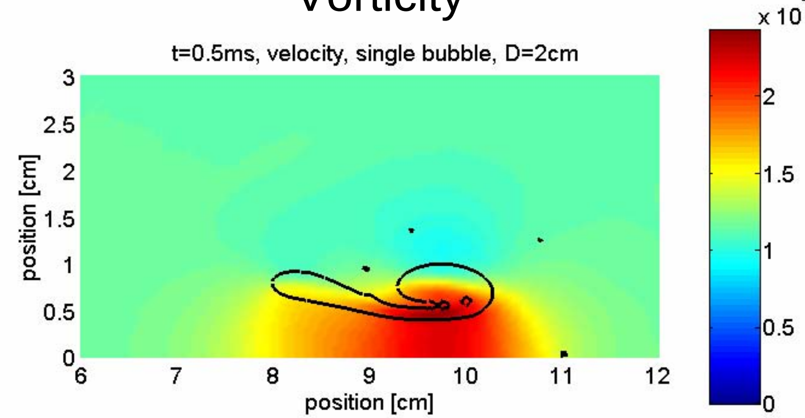
(d) The vortex ring is formed.

Properties of a single bubble

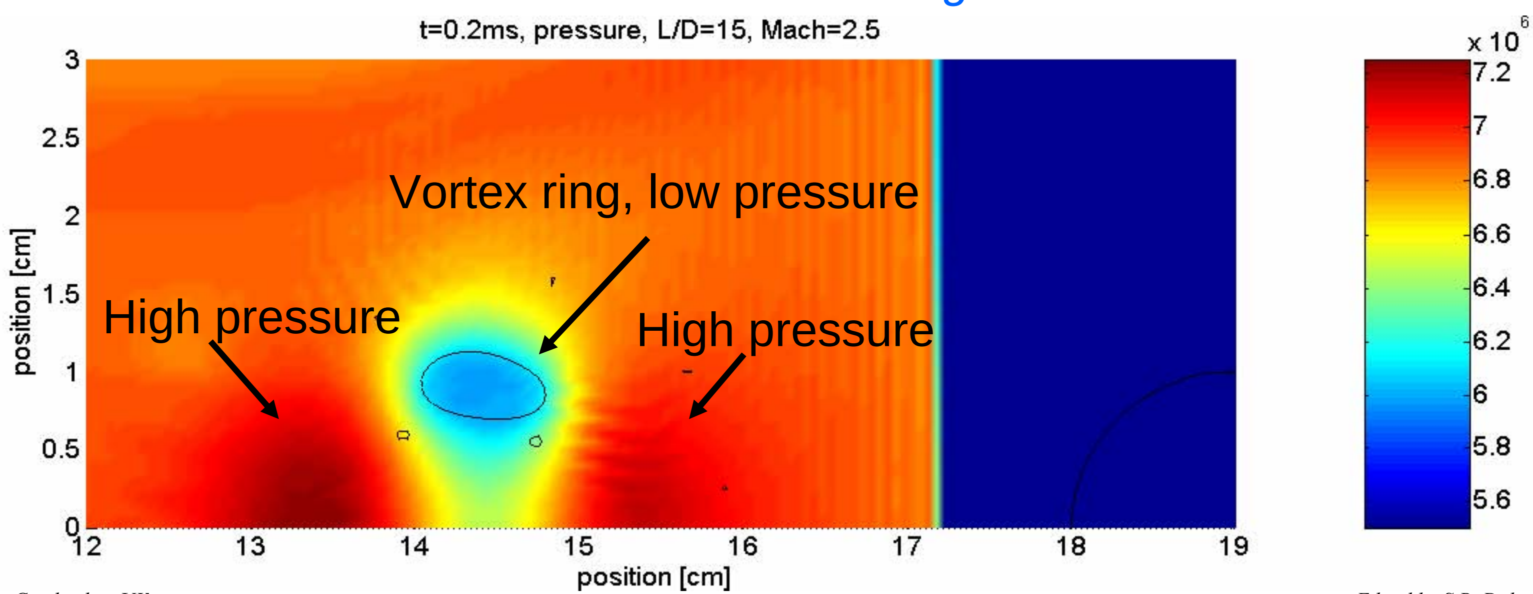
horizontal axis velocity



Vorticity

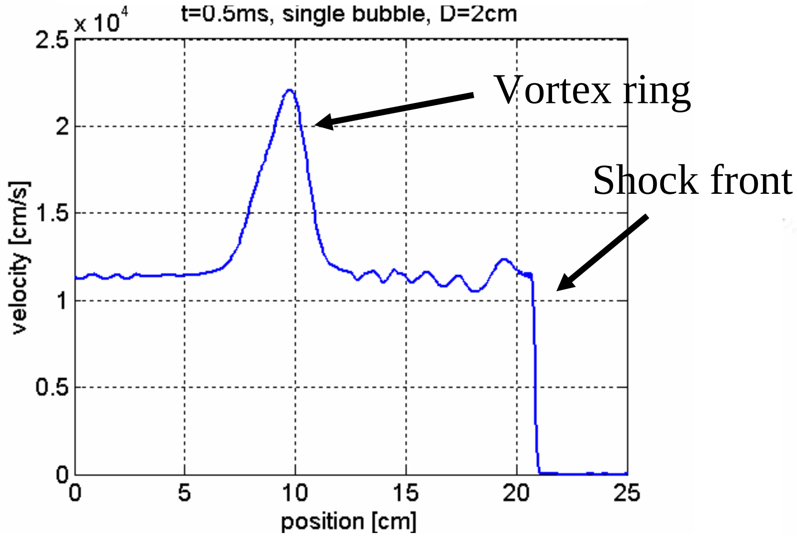


Pressure around a vortex ring

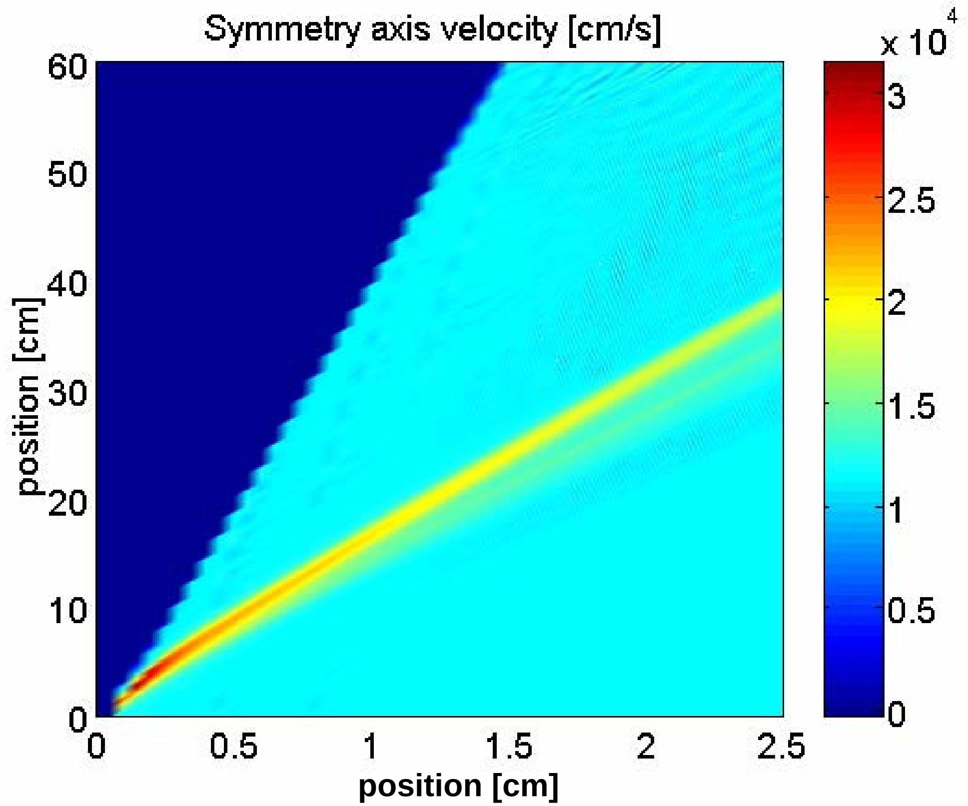


Single bubble – velocity profile

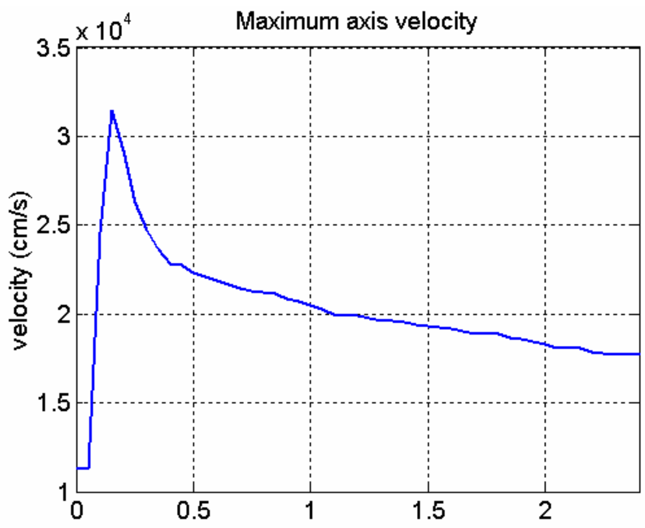
Symmetry axis velocity



The maximum velocity is the location of the center of the vortex ring



Maximum velocity on the symmetry axis

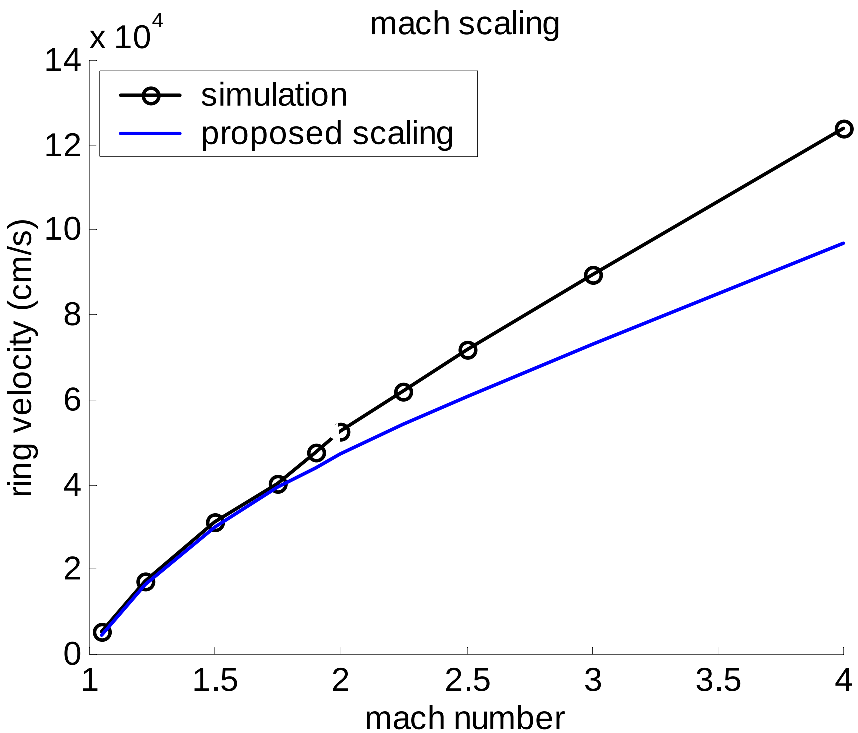


Scaling in the shock bubble interaction Dimensional analysis

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
Γ – circulation
η – density ratio
γ – specific heat ratio
c_s – speed of sound

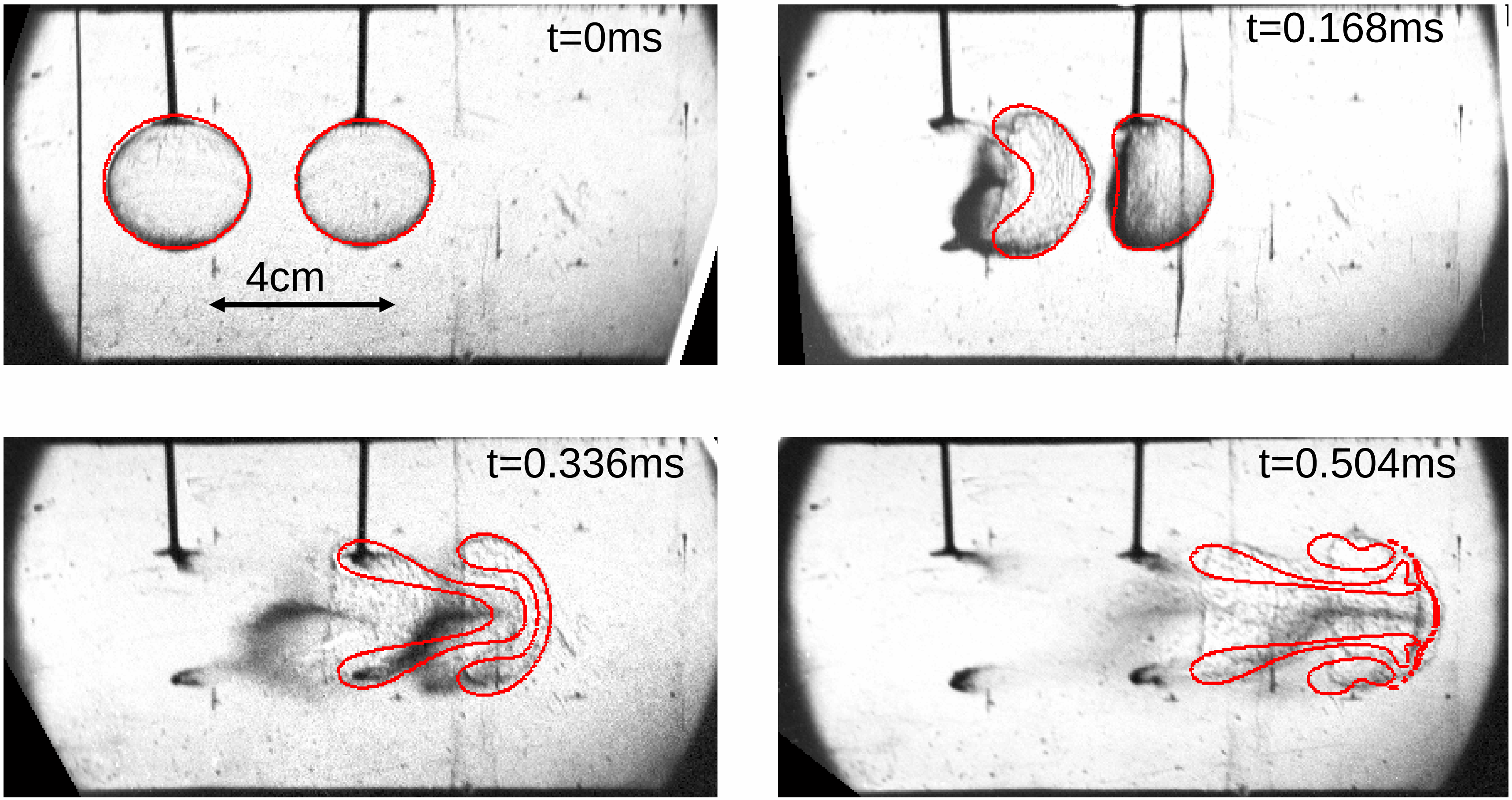
Samtaney & Zabusky, JFM. **269** (1994)

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

- Good agreement is found for M<2.

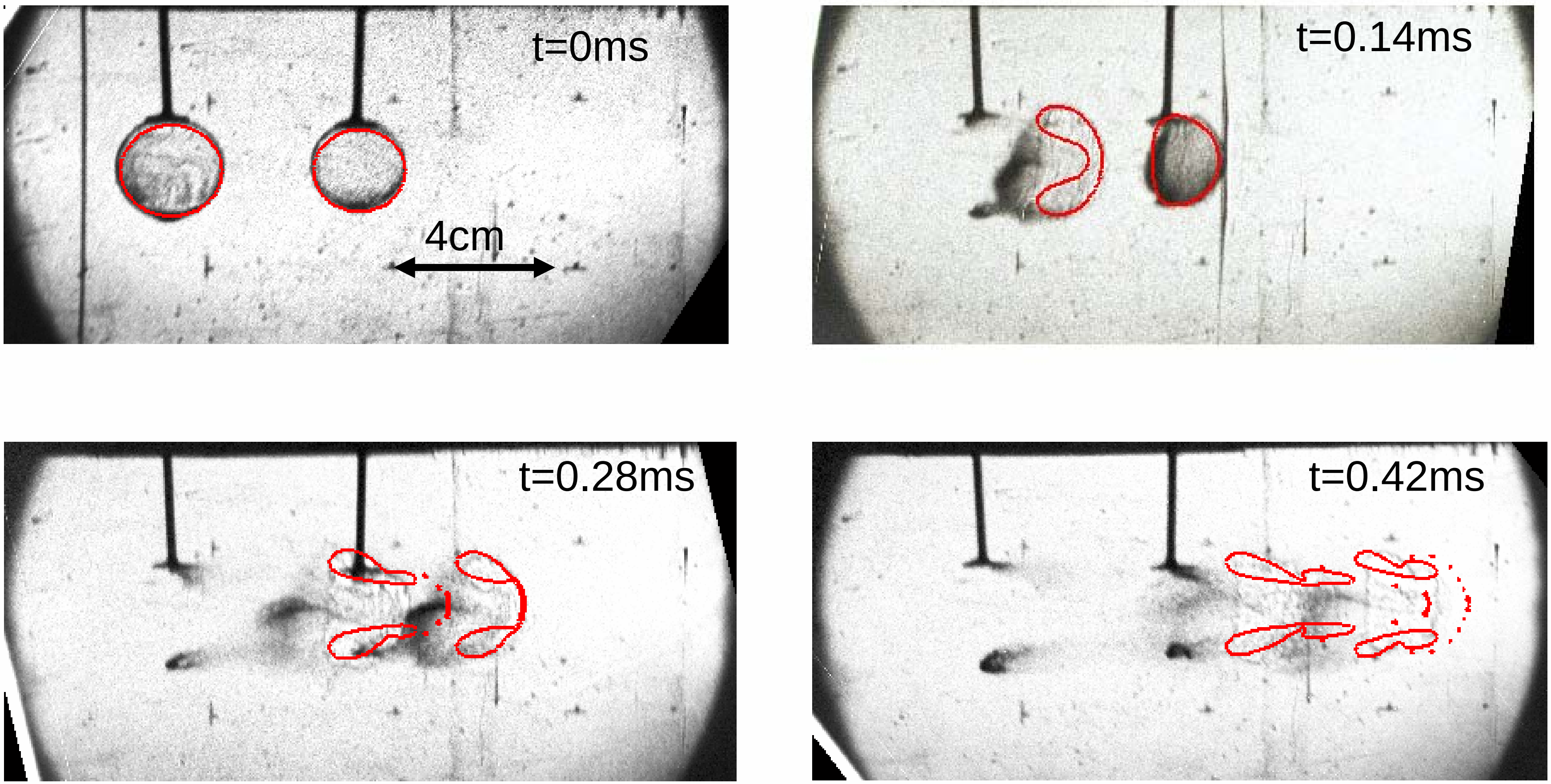
Two bubbles, L/D=1/3, (D=3cm)

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



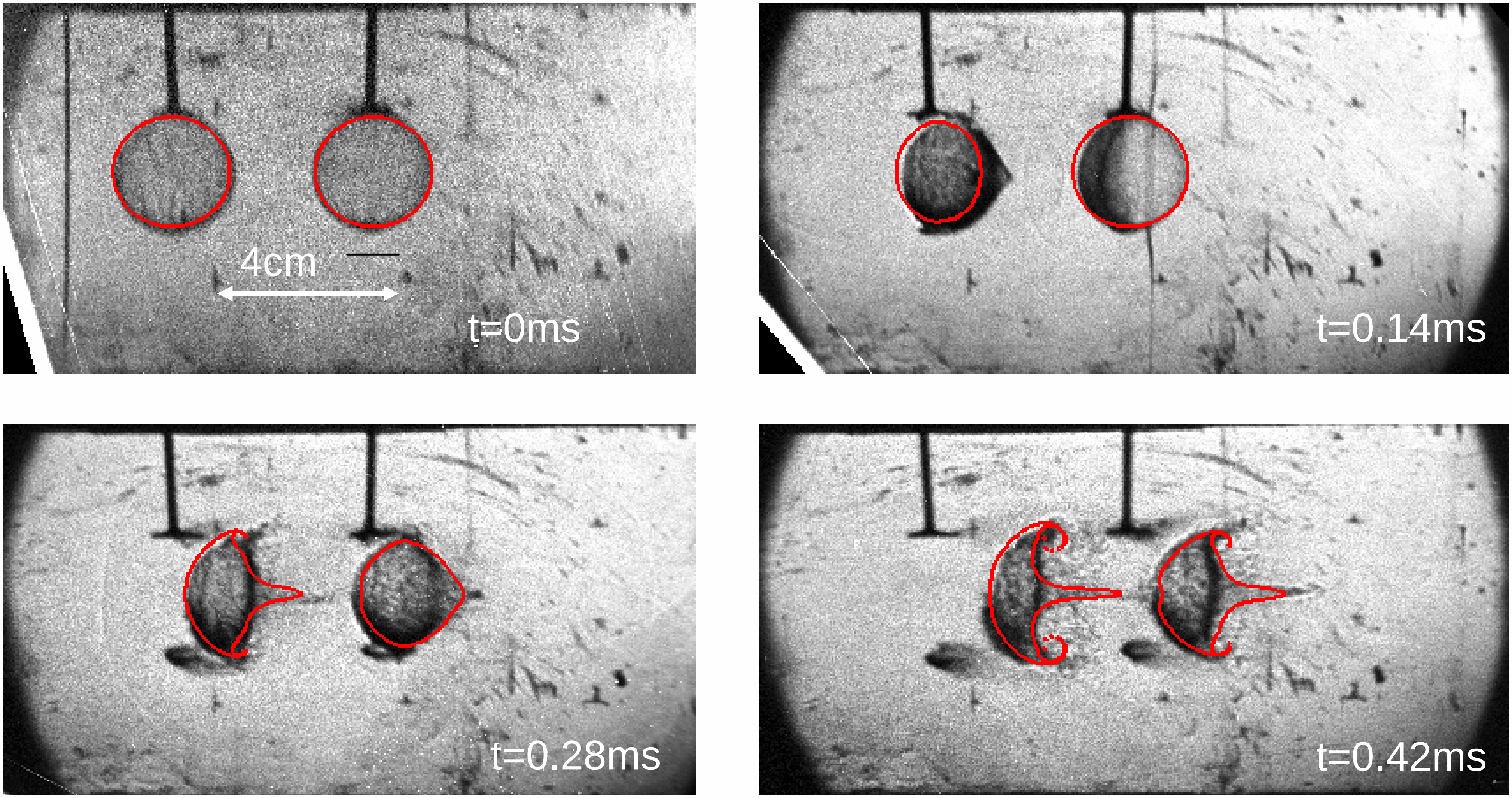
Two bubbles, L/D=1, (D=2cm)

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



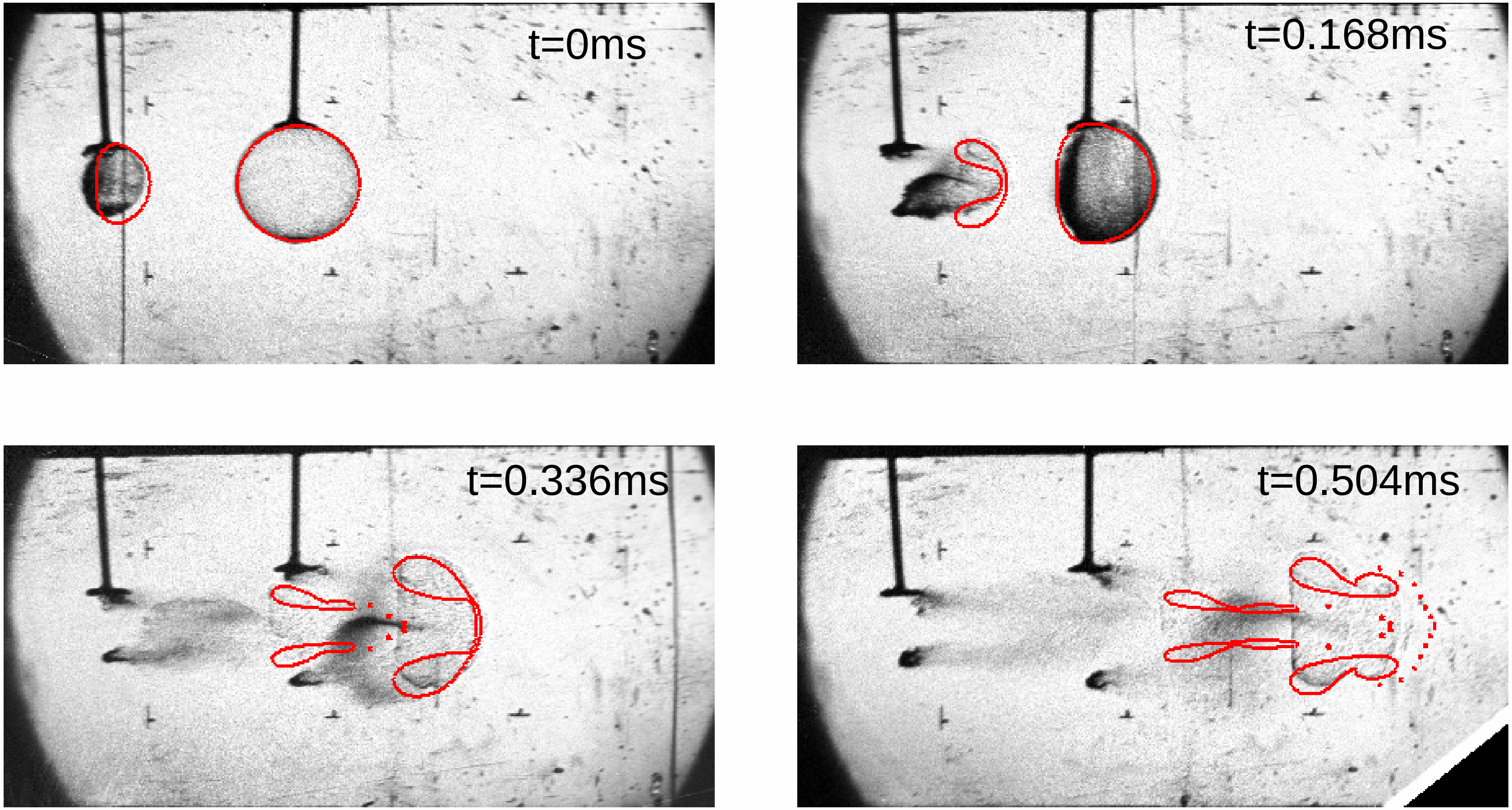
Two bubbles, L/D=2/3, (D=3cm)

fast/slow (air-SF_6), mach=1.22



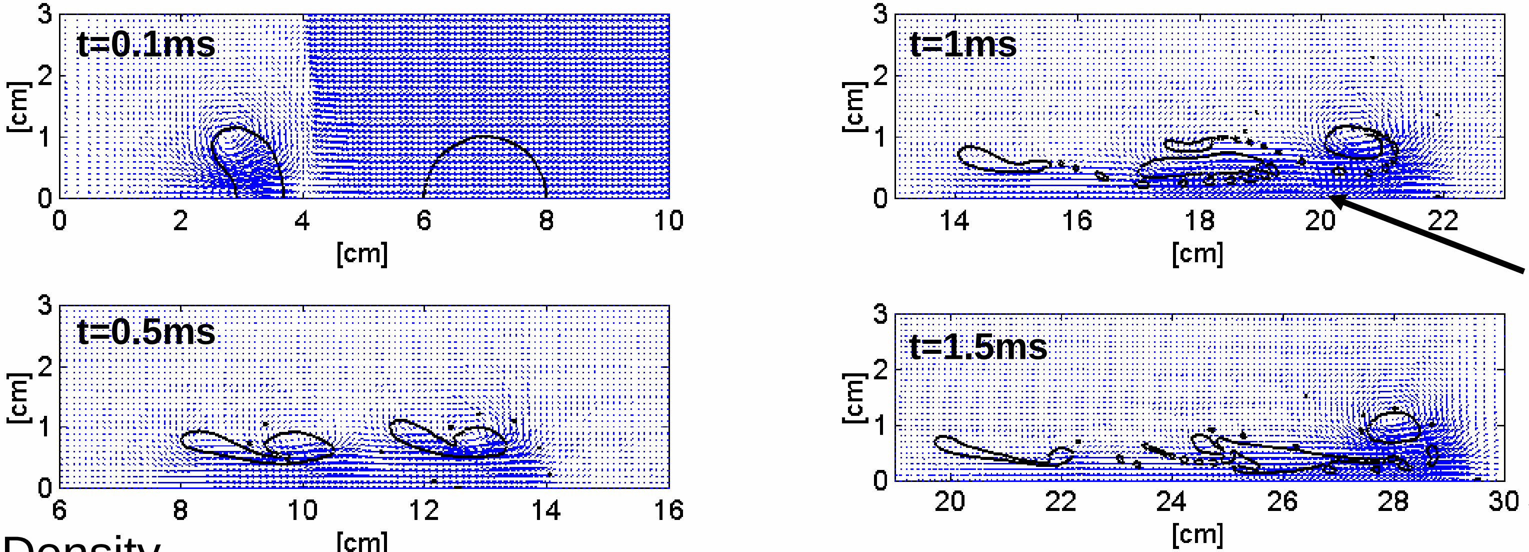
Two bubbles, ratio 1.6, L/D=0.75, (D=2.6cm)

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



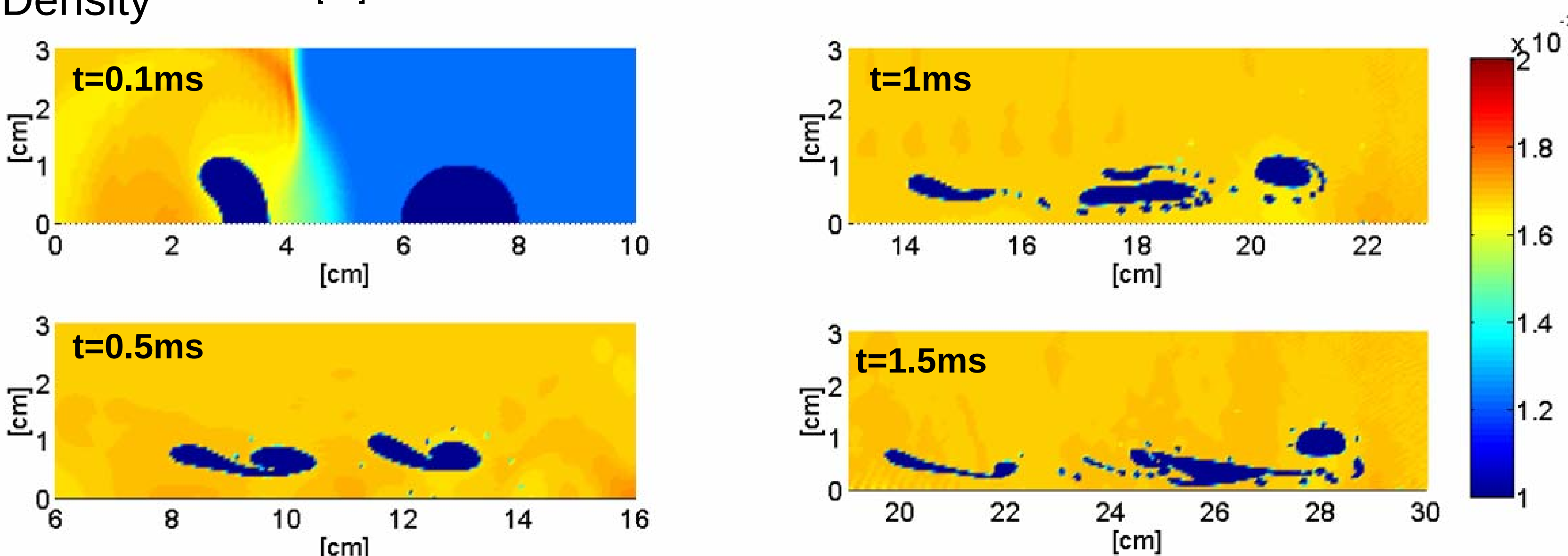
Typical Simulation - L/D=1.5 (D=2cm)

Velocity field



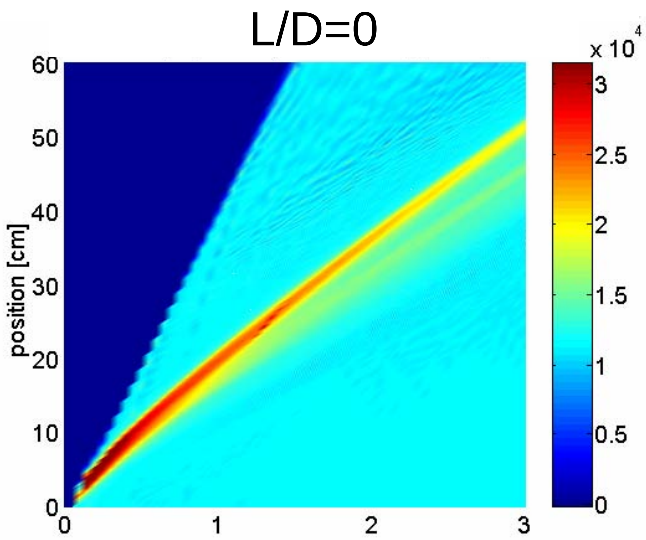
- deformation of upstream vortex ring
- Suction of upstream vortex into the downstream vortex

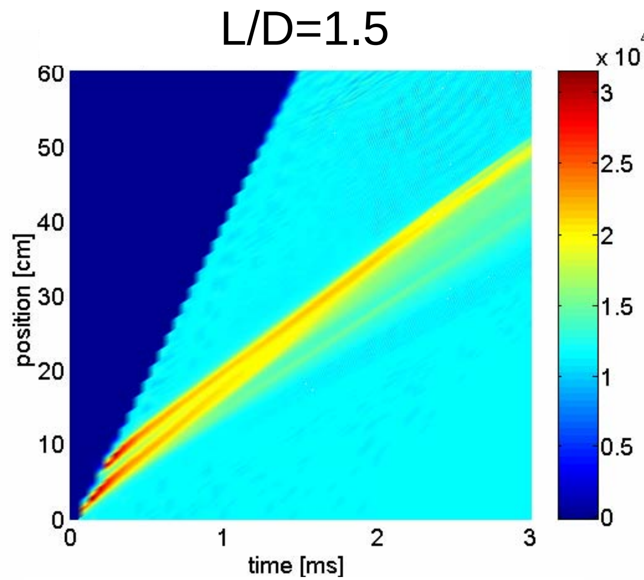
Density



Symmetry axis velocity profile

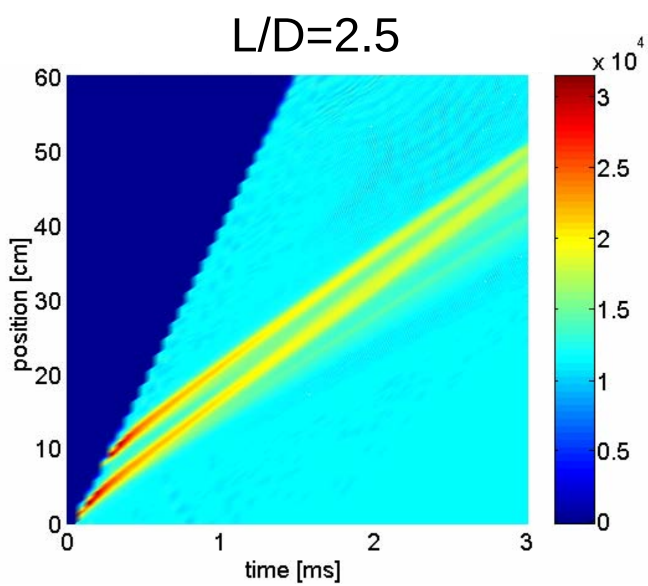
Early interaction:
No period of two co-existing vortex rings

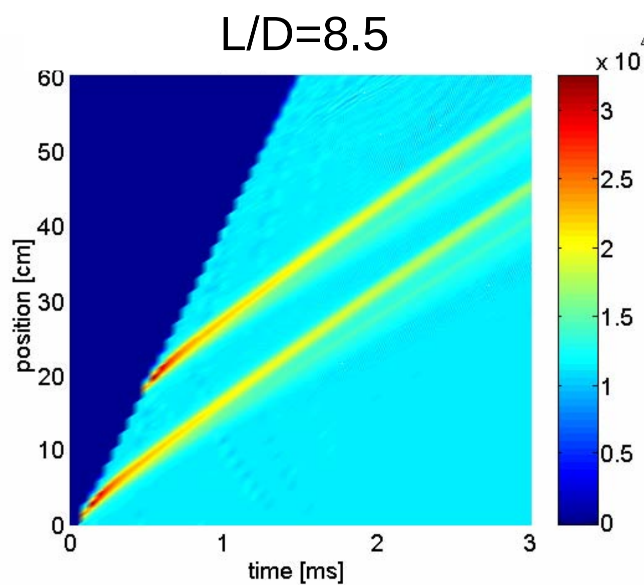




Moderate interaction
The vortex ring interact shortly after formation

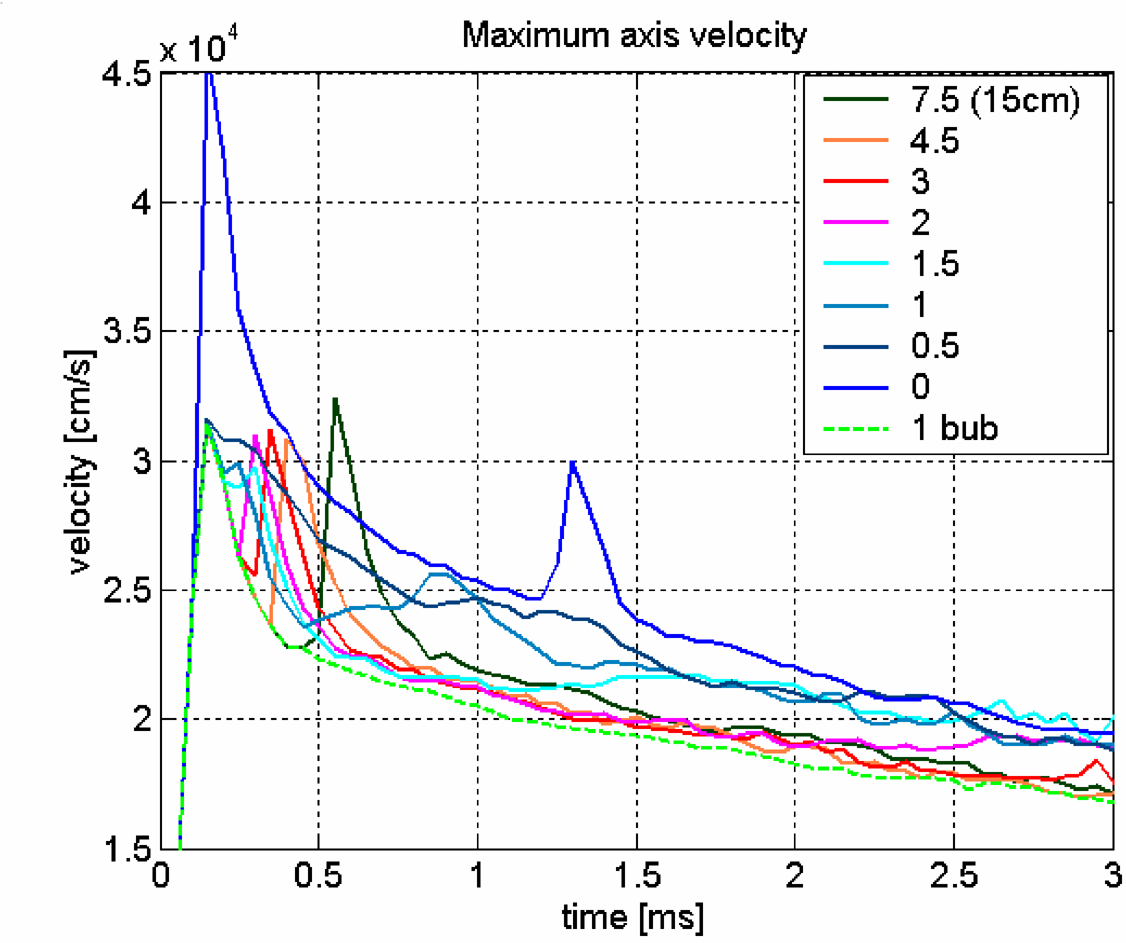
Late interaction
Vortex rings flow interdependently for a significant period





No interaction
according to prediction based on the vortex ring velocity

Maximum velocity on axis



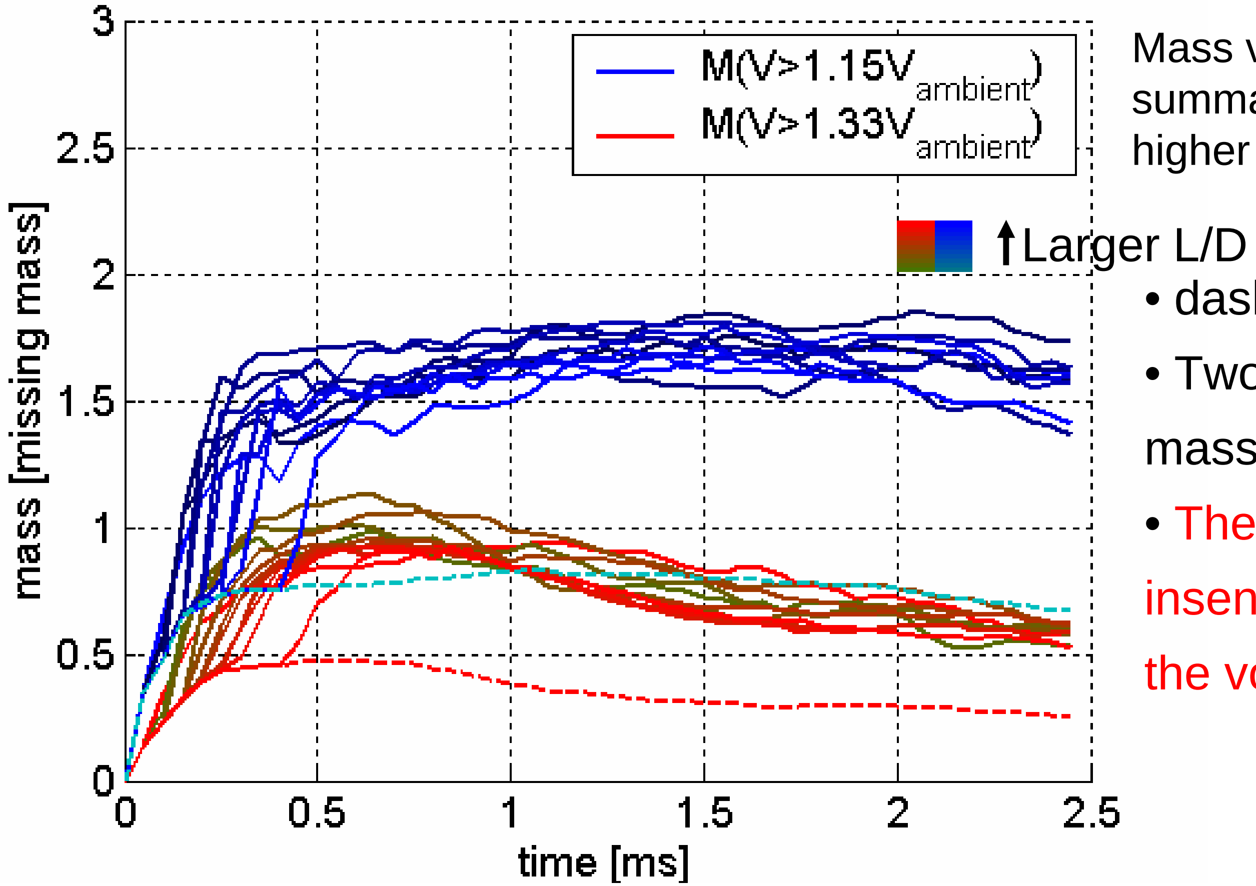
Dashed line – single bubble

Maximum velocity when **interaction exists**

Maximum velocity when there is **no interaction**

- 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

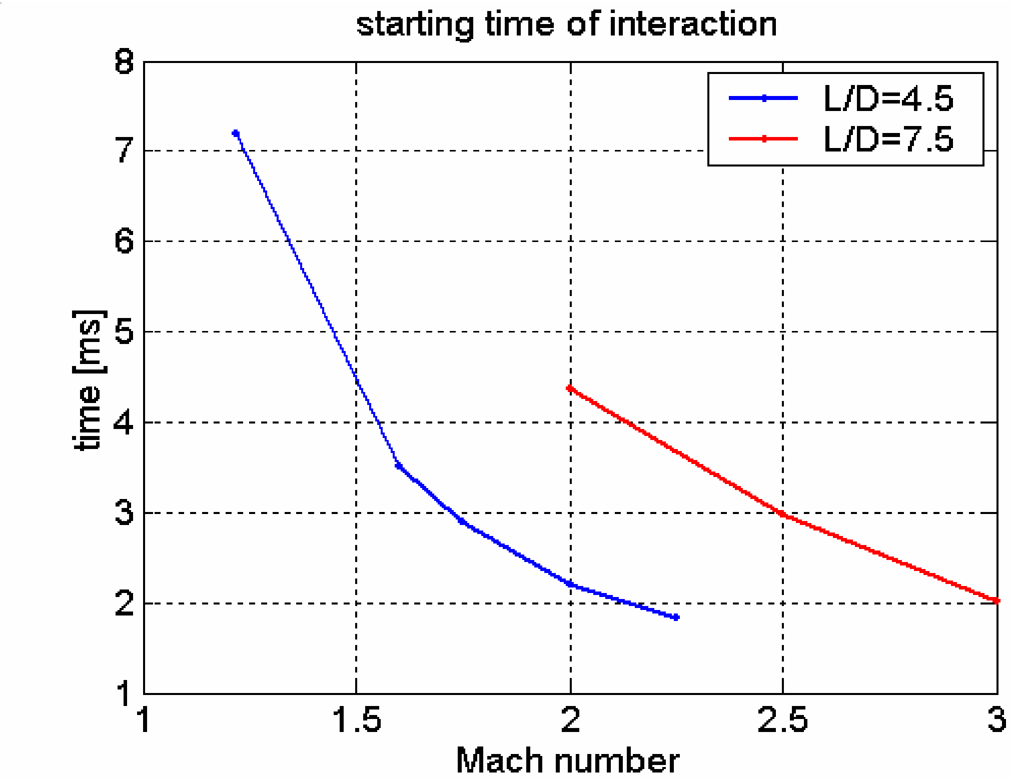
Mass velocity criterion



Mass velocity criterion:
summation of the mass with velocity higher then 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

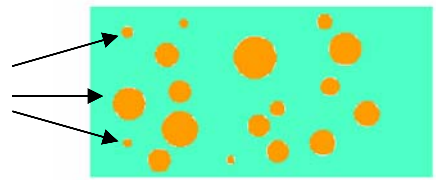


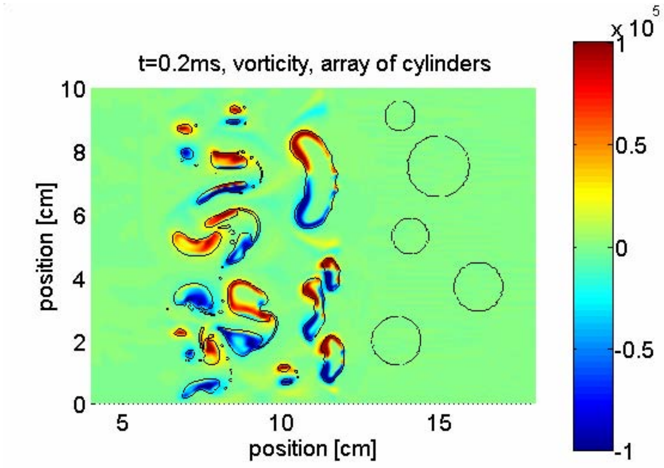
- Higher Mach number => the interaction occurs earlier
- L/D=4.5: Mach higher than 2.5 – merger before formation of second vortex ring.

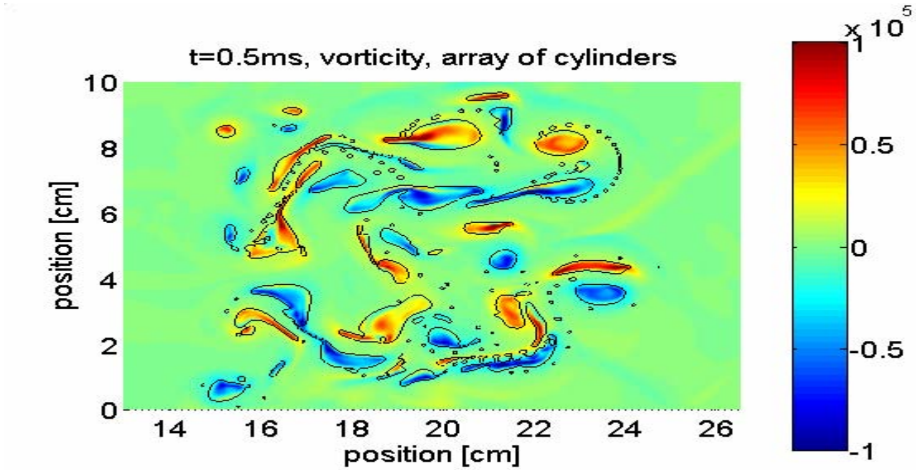
Random array of cylindrical bubbles

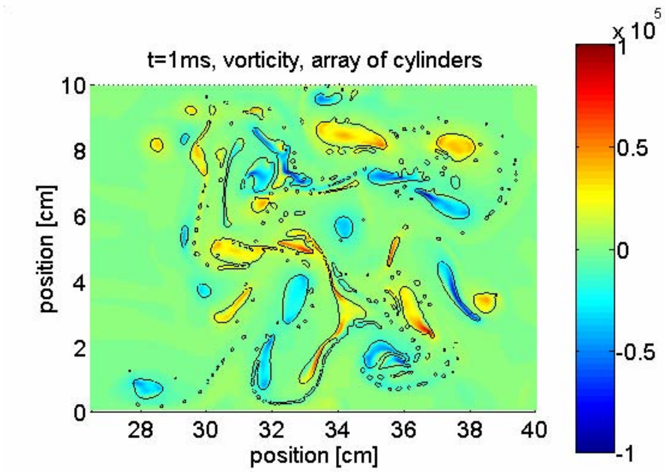
Vorticity

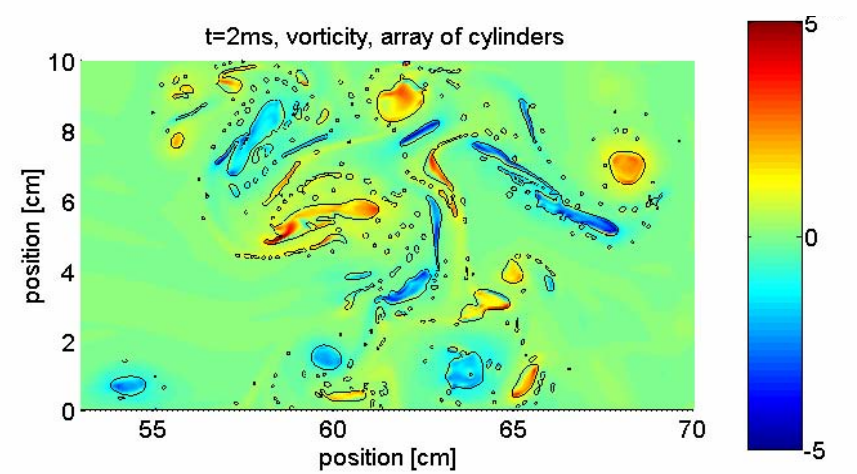
Randomly distributed cylinders











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.