Experimental study of the interaction of a planar shock with a free rising bubble

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Shock-bubble interaction: previous and current work

Previous experimental studies:

- Bubble gases: He, Ar, Kr, R22
- Density contrast: $-0.75 \leq \text{At} \leq 0.5$
- Shock strengths: $1.05 \leq M \leq 4$
- Film material

Previous numerical studies:

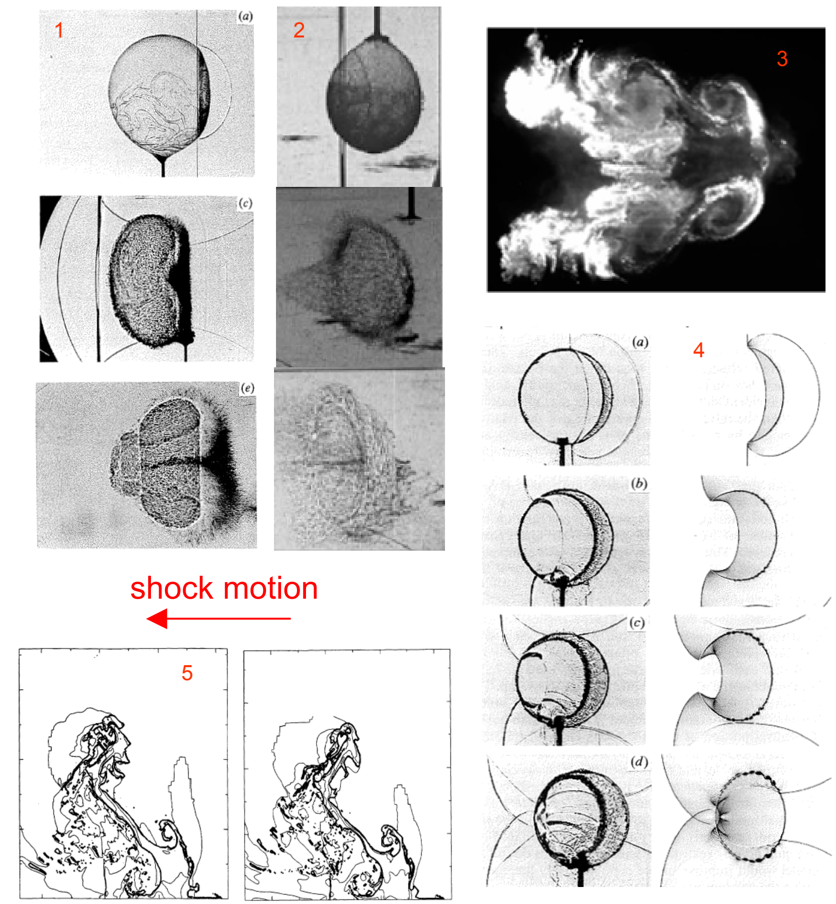
- Euler equations
- 2D resolution: $R_{30} - R_{900}$
- 3D resolution: R_{90}
- Methods: FCT, TVD, Godunov, WENO
- Adaptive gridding

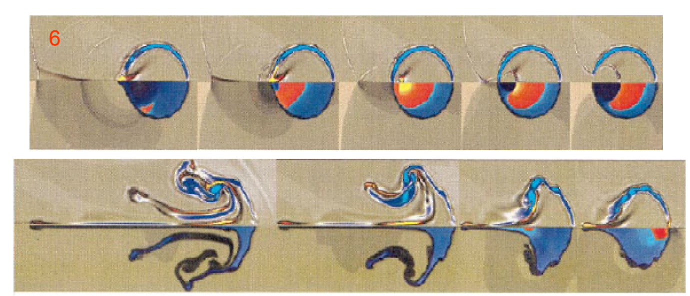
Previous 2D numerical parameter studies:

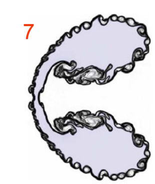
- Astrophysical regime, R_{120}
- Shock tube regime, R_{50}

Current study:

- Shock strengths: $1.45 \leq M \leq 3$
- Density contrast: $\text{At} = -0.75$
- Planar imaging and free flow bubble



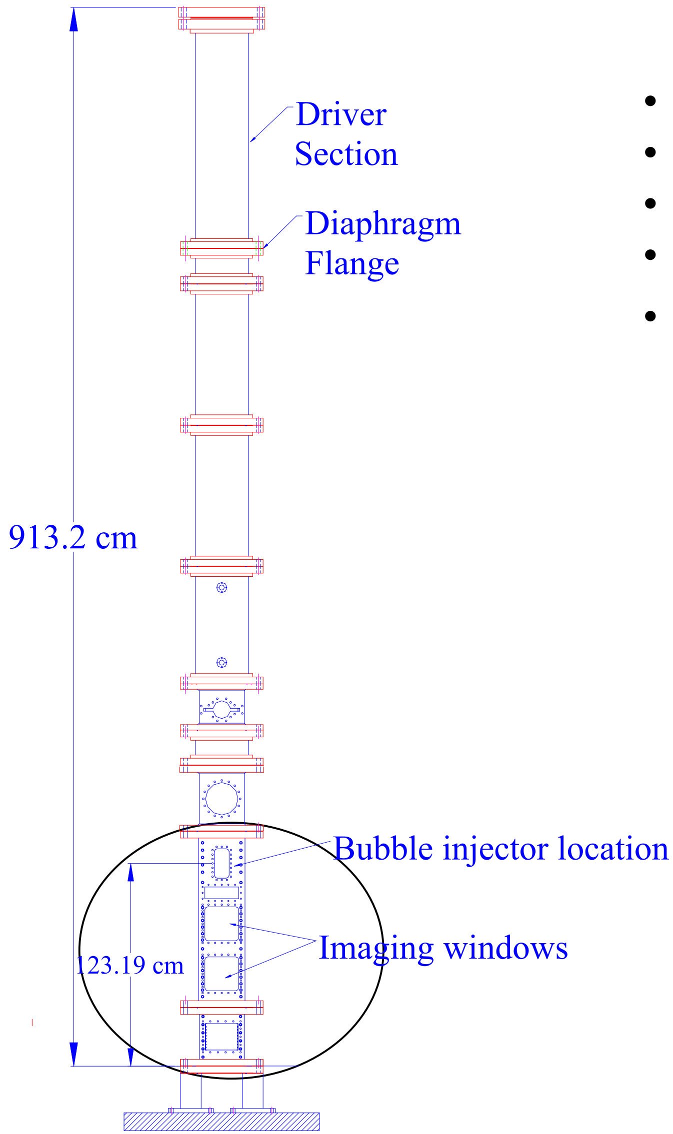


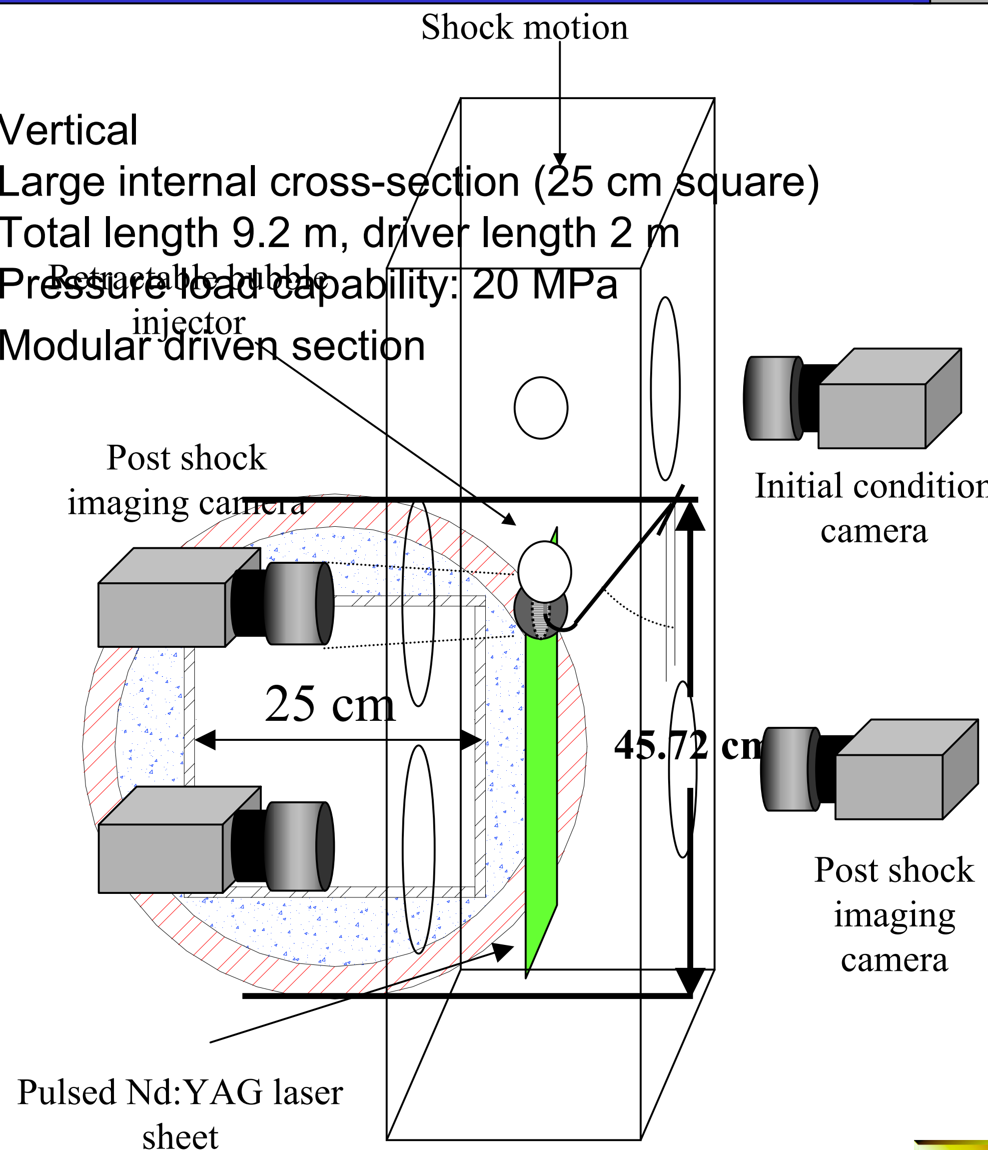


1. Haas and Sturtevant, *JFM*, 1987
2. Layes, et al., *PRL*, 2003
3. Ranjan et al., *PRL*, 2005
4. Quirk and Karni, *JFM*, 1994
5. Klein, et al., *Ap.J.*, 1994
6. Zabusky and Zeng, *JFM*, 1998
7. Marquina and Mulet, *JCP*, 2003

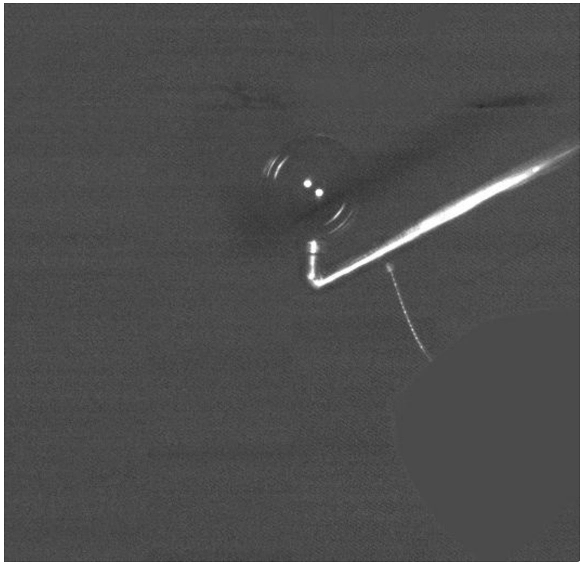
Experimental setup: initial condition

- Vertical
- Large internal cross-section (25 cm square)
- Total length 9.2 m, driver length 2 m
- Pressure load capability: 20 MPa
- Modular driven section

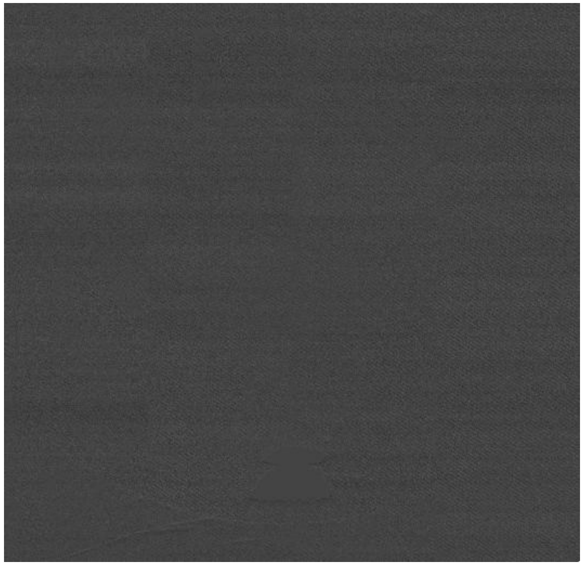




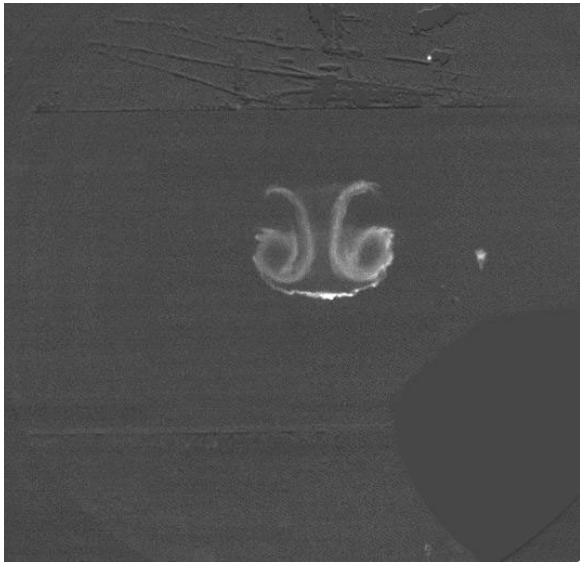
Initial condition: bubble in free flow, 100 fps (shown at 5 fps)



Bubble release in lower IC window

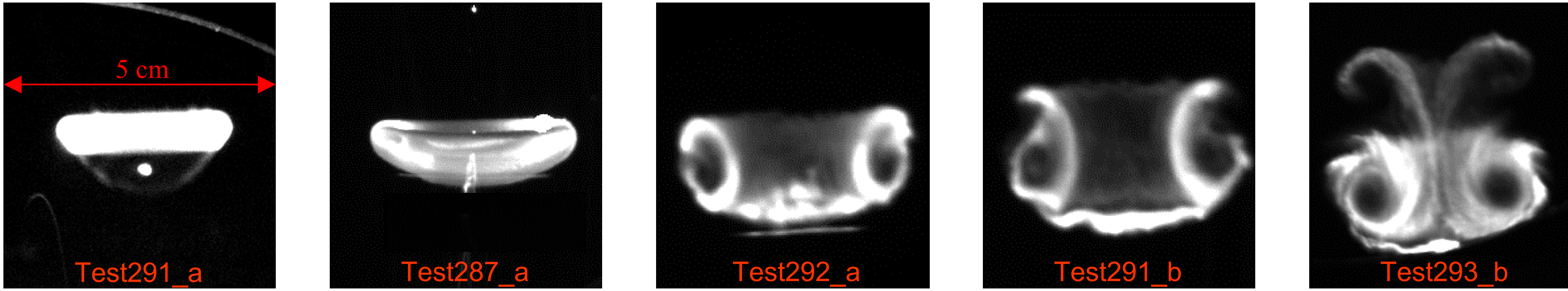


Bubble rises into upper IC window and stabilizes into sphere

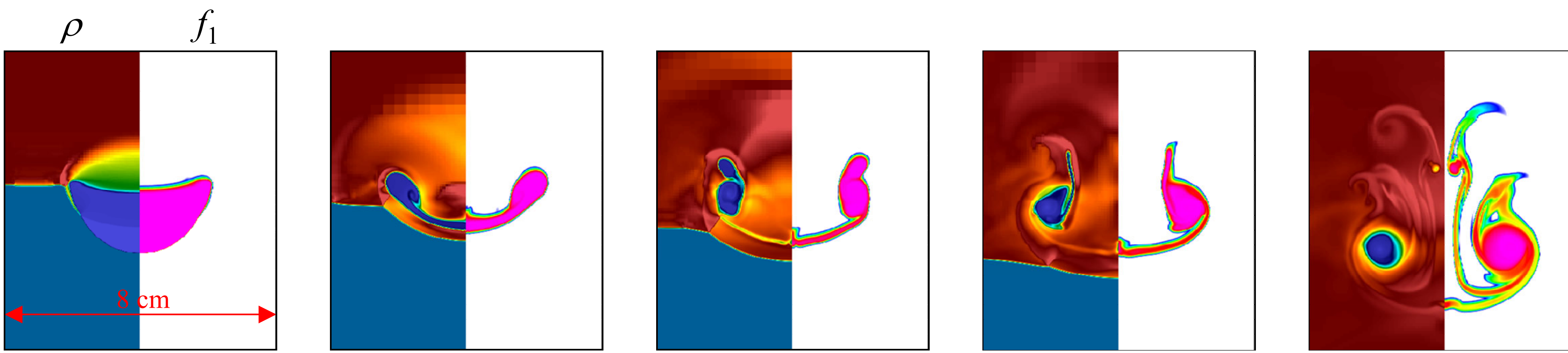


Shocked bubble imaged in the lower IC window

Flow visualization: high Mach number , M=2.95



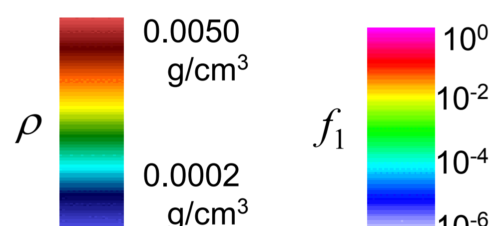
t = 13 μs, t/τ = 1.3 | t = 35 μs, t/τ = 4.0 | t = 70μs, t/τ = 7.7 | t = 113 μs, t/τ = 11.6 | t = 230 μs, t/τ = 23.8



t = 12.7 μs, t/τ = 1.3 | t = 40.5 μs, t/τ = 4.1 | t = 75.3 μs, t/τ = 7.7 | t = 112.2 μs, t/τ = 11.5 | t = 230.7 μs, t/τ = 23.6

Bubble gas: He
Ambient gas: N_2
At = - 0.75

$$\tau = \frac{D}{2 W_{tr}}$$



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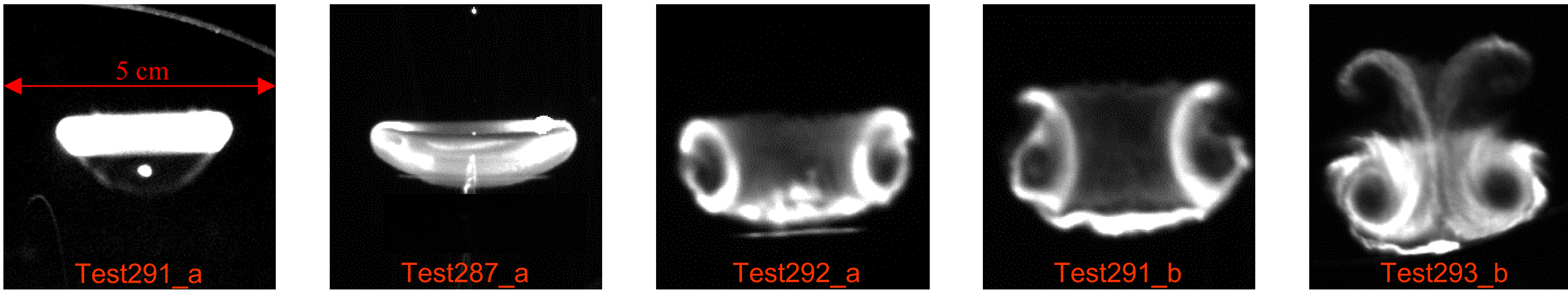

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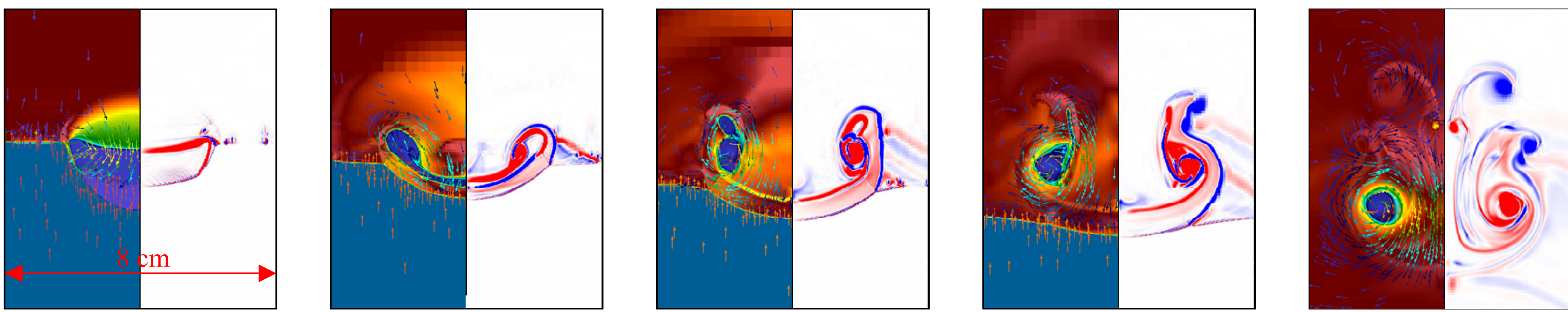
$\vec{U}'$ ω



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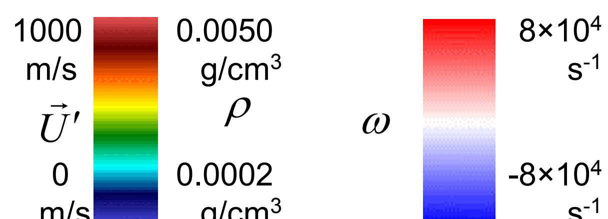
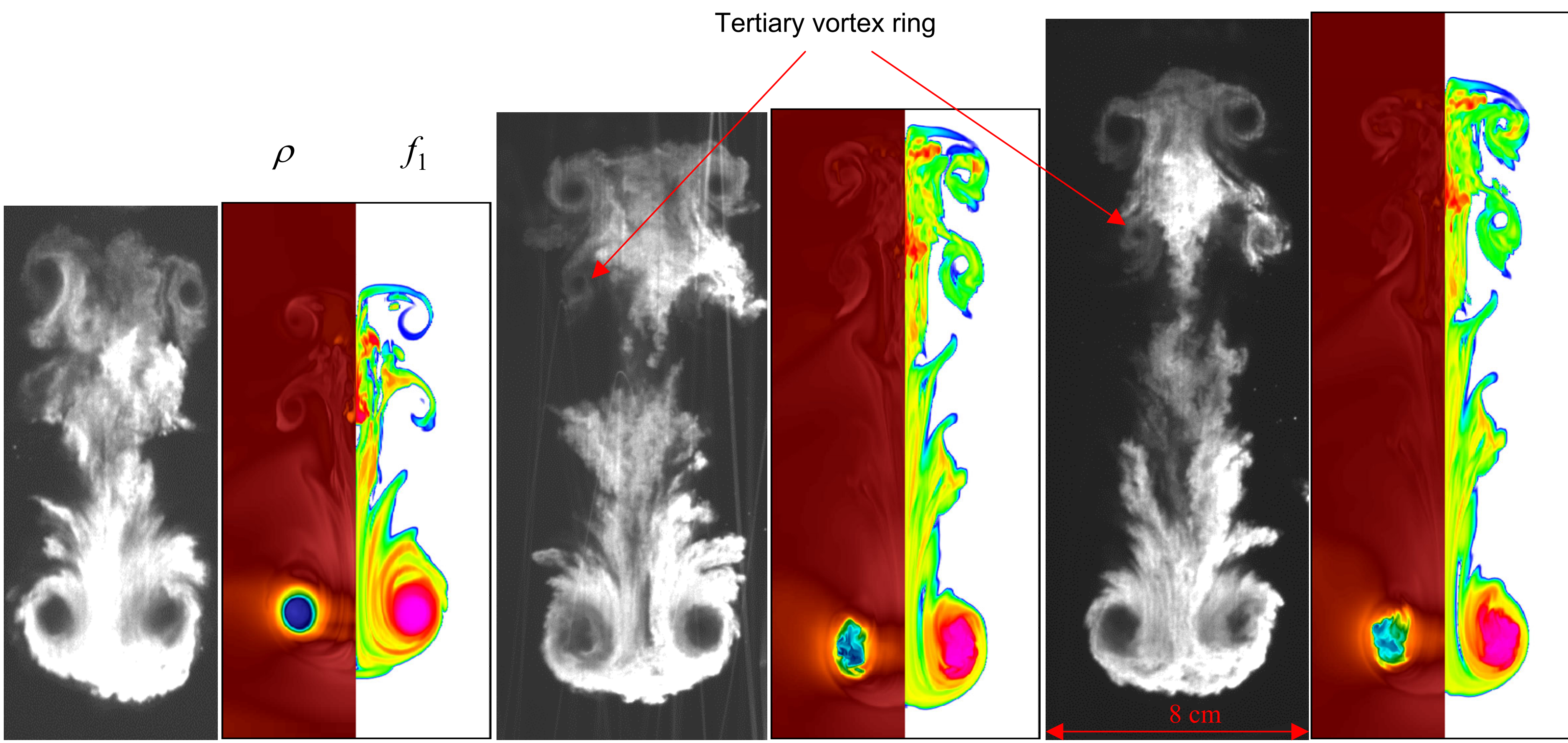
Bubble gas: He
Ambient gas: N_2
At = - 0.75

$$\tau = \frac{D}{2\,W_{tr}}$$

$$\vec{U}' \equiv \vec{U}(x,y,z) - u_2\hat{y}$$



Flow visualization: high Mach number , M=2.95



t = 430 μs, t/τ = 46.3

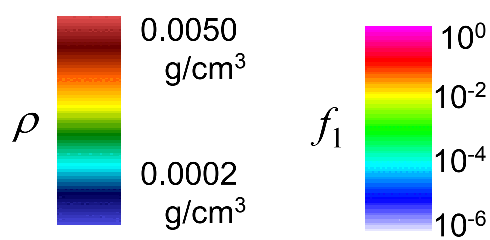
t = 445.6 μs, t/τ = 45.6

t = 721 μs, t/τ = 63.5

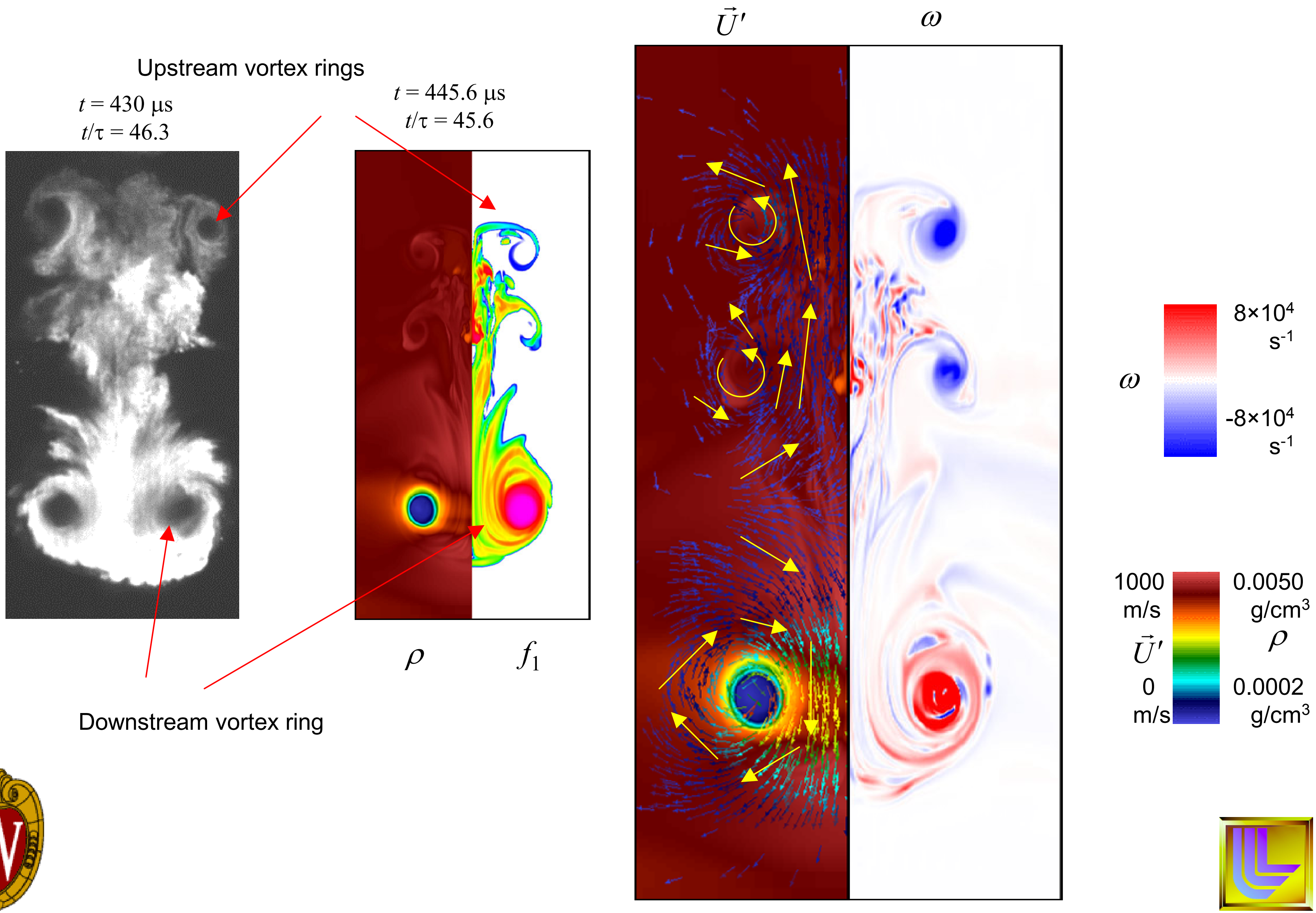
t = 620.9 μs, t/τ = 63.5

t = 725 μs, t/τ = 69.5

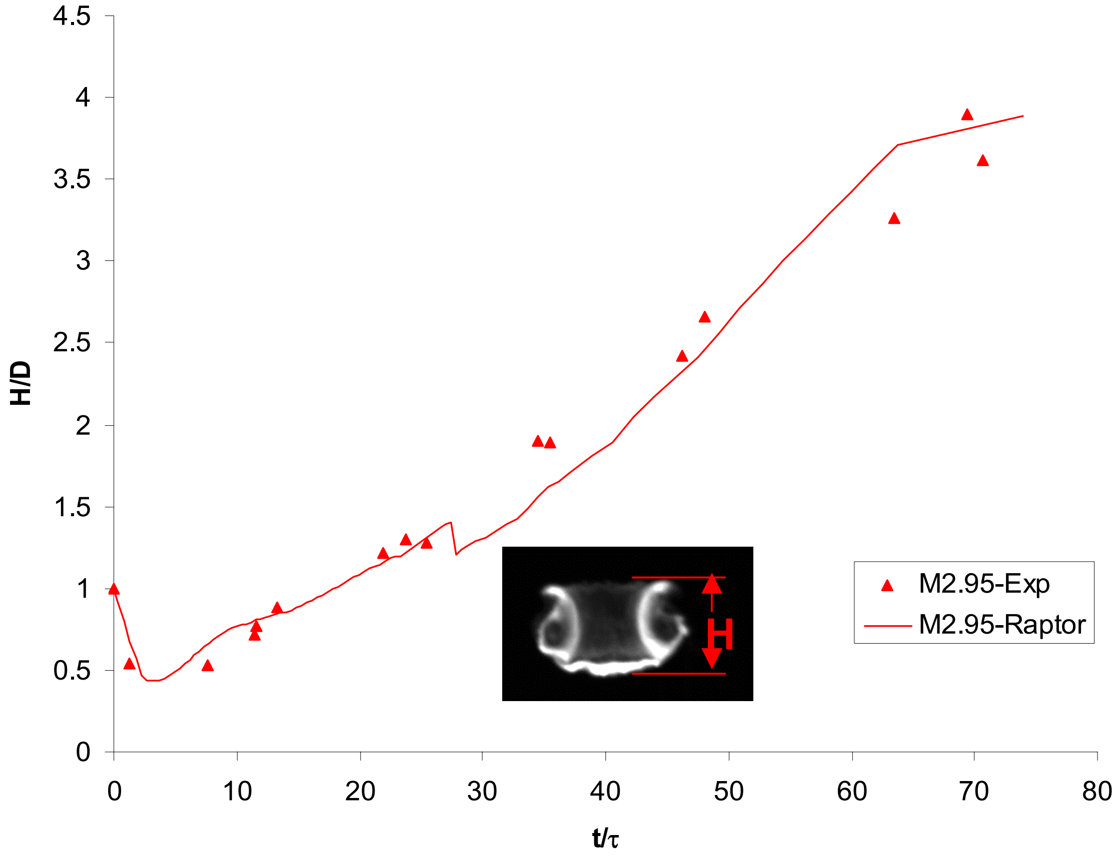
t = 699.7 μs, t/τ = 71.6



Flow visualization: high Mach number , M=2.95



Integral diagnostics: axial bubble dimension



$$\tau = \frac{D}{2W_{tr}}$$

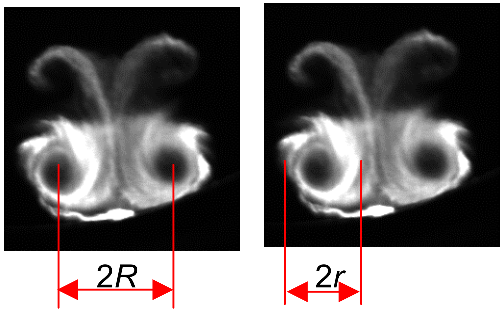
Integral diagnostics: circulation

$$\Gamma_K = \frac{4\pi R\left(V_V - u_p\right)}{\ln\left(\frac{8R}{r}\right) - \frac{1}{4}}$$

Circulation of a moving vortex ring

(V_V = vortex velocity, u_p = particle velocity, $2R$ = major diam., $2r$ = minor diam.)

(Kelvin, 1867)



$$\Gamma_{PB} \approx u_p\left(1 - \frac{u_p}{2V_w}\right)D\ln\left(\frac{\rho_\infty}{\rho_b}\right)$$

Upper bound for shock-generated ring

(u_p= particle velocity, V_W= shock velocity, D= initial bubble diameter,)

(Picone & Boris, *JFM* 1988)

$$\Gamma_{YKZ} \approx \frac{2D}{V_w}\left(\frac{p_2 - p_0}{\rho_2}\right)\left(\frac{\rho_b - \rho_\infty}{\rho_b + \rho_\infty}\right)$$

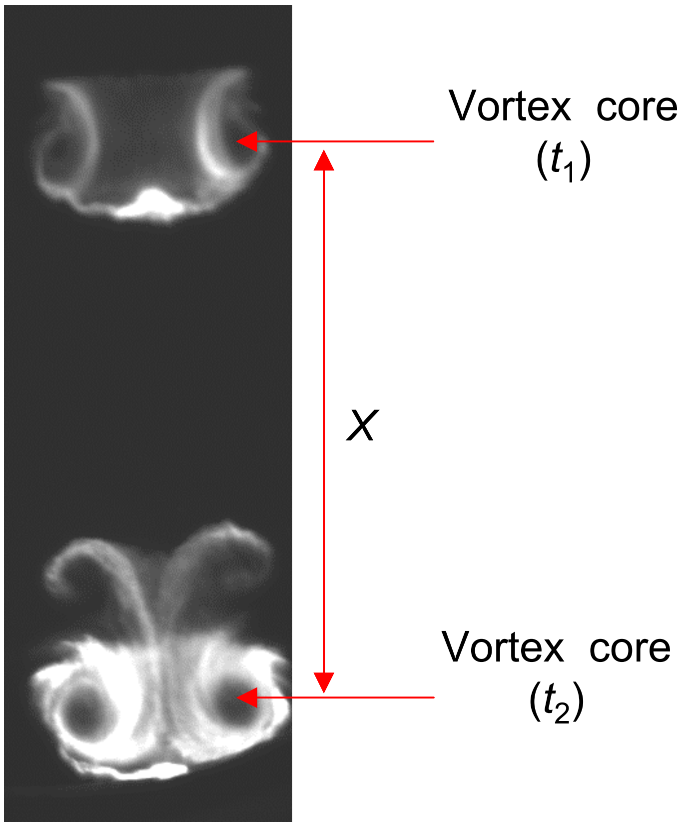
Upper bound for shock-generated ring

(p_0= initial pressure of unshocked ambient gas, p_2= pressure of shocked ambient gas, ρ_2= density of shocked ambient gas)

(Yang, Kubota & Zukoski *JFM* 1994)

Integral diagnostics: vortex ring velocity

	Vortex ring velocity Downstream (V/U_p)		Vortex ring velocity Upstream (V/U_p)	
t/τ	Exp	Raptor	Exp	Raptor
11.58	1.13	1.17	0.85	0.91
23.8	1.16	1.15	0.95	0.99
25.4	1.15	1.16	0.96	0.98
31.56	1.11	1.19	-------	0.97
46.26	1.18	1.25	0.97	0.92



$V = X/(\Delta t)$

- ***M* = 2.95 : U_p = 768 m/s**

Integral diagnostics: circulation

			Downstream (primary)				Upstream (secondary)	
t/τ	**U_p (M)**	**D**	Γ_{exp}	Γ_{PB}	Γ_{YKZ}	Γ_{Rap}^{+}	Γ_{exp}	Γ_{Rap}^{-}
	m/s	cm	m^2/s	m^2/s	m^2/s	m^2/s	m^2/s	m^2/s
11.58	755 (2.91)	3.81	15.1	35.4	11.45	28.0	-----	-7.3
23.8	**768 (2.95)**	**3.81**	**20.9**	**35.9**	**11.54**	**22.6**	**-5.2**	**-1.4**
25.4	765 (2.94)	3.25	14.9	30.6	9.83	19.4	-3.1	-1.2
31.56	755 (2.91)	3.81	11.3	35.4	11.45	22.8	------	-1.5
46.26	775 (2.97)	3.68	23.3	35.0	11.18	21.3	------	-1.8

Integral diagnostics: circulation

			Downstream (primary)				Upstream (secondary)	
t/τ	U_p (M)	D	Γ_{exp}	Γ_{PB}	Γ_{YKZ}	Γ_{Rap}^{+}	Γ_{exp}	Γ_{Rap}^{-}
	m/s	cm	m^2/s	m^2/s	m^2/s	m^2/s	m^2/s	m^2/s
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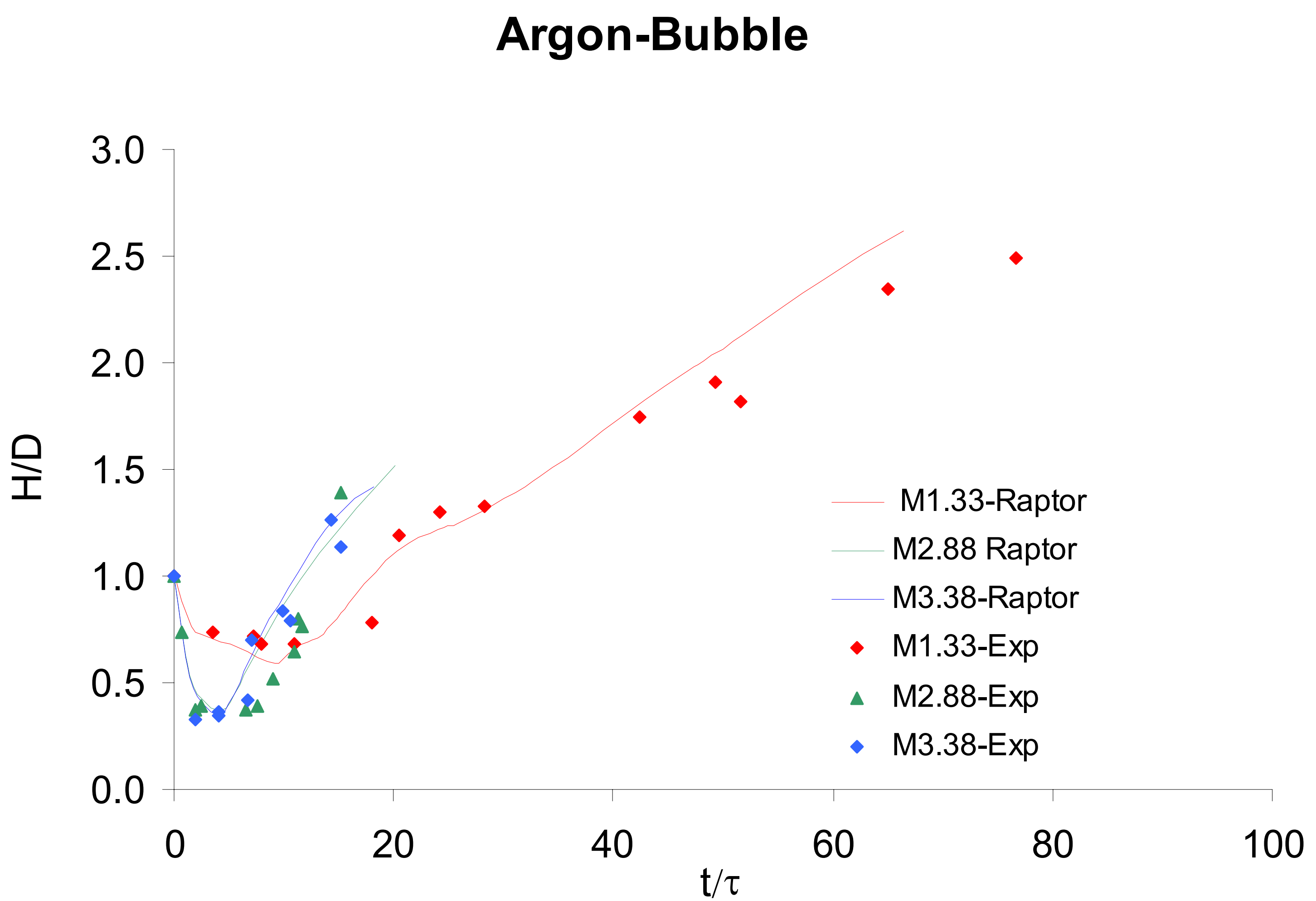
Argon-Bubble
3.0
2.5
2.0
1.5
1.0
0.5
0.0
H/D
0
20
40
60
80
100
t/τ
M1.33-Raptor
M2.88 Raptor
M3.38-Raptor
M1.33-Exp
M2.88-Exp
M3.38-Exp

Conclusions and future work

- Experimental technique : Successful high Mach number experiments with planar imaging and free flow bubble are performed.
- Comparison to simulations : Salient flow features are captured in both experiments and simulations.
- Bulk properties of bubble growth : Spatial extent, circulation & vortex ring velocity are predicted with mixed success by simulation and various models.
- Secondary features : Strong counter-rotating secondary and tertiary vortex rings are observed at $M > 2$.
- Mach number effects : Transition in bubble growth trends is observed at $M \sim 2$.

Future Work:

- Carry out experiments in M>2 , At>0.5 regime.
- Develop experiments to measure species concentration.