Karlsruhe Institute of Technology

ANALYSIS OF HIGH-SPEED LITHIUM JET FLOW UNDER VACUUM CONDITIONS

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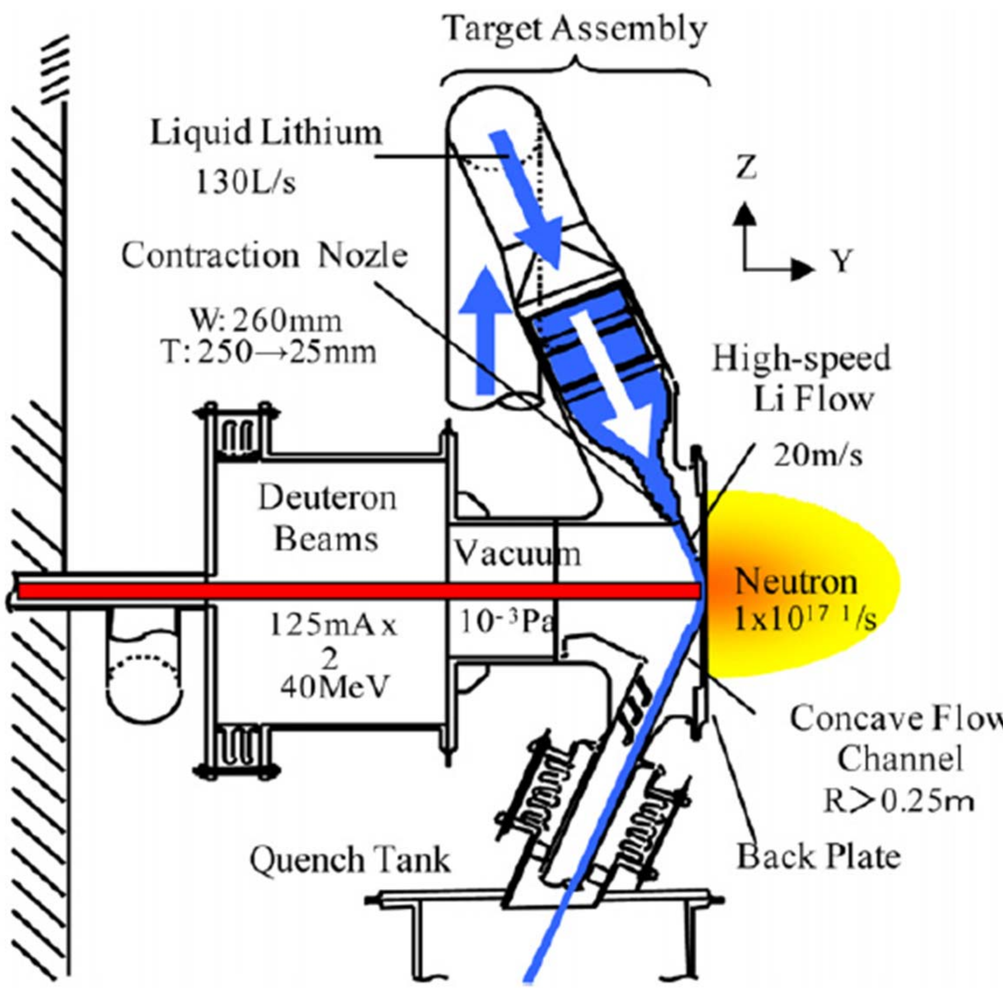
CONTENT

- Int. Fusion Material Irradiation Facility (IFMIF)
  - Development
  - Validation strategy
  - Recent observations – Motivation
- Numerical Simulation
  - Description of numerical model
  - Validation of model assumption by experiments
  - Transfer to a lithium jet
- Analysis target flow
- Summary and Outlook

IFMIF Li Target-Development

Concept of Li IFMIF (Int. Fusion Materials Irradiation Facility) Target



Goal

- Generation of high-energy neutron flux (simulating fusion typical flux and neutron spectrum)
- Neutron generation by Deuteron (D+)–Lithium (**Li**) nuclear reaction within a target (2x40MeVx125mA) ➨10 MW target power.

Target:

- High speed free-surface liquid Li stream (15-20 ms^{-1})
- Upflow conditioning double-contraction nozzle
- Free surface flow along concave duct
- Ambient pressure 10^{-3} Pa.

Requirements

- Stable Li-film thickness
- Mechanical robustness of target system

IFMIF Li-target validation

Validation of feasibility IFMIF within Broader Approach Agreement JAEA – EU

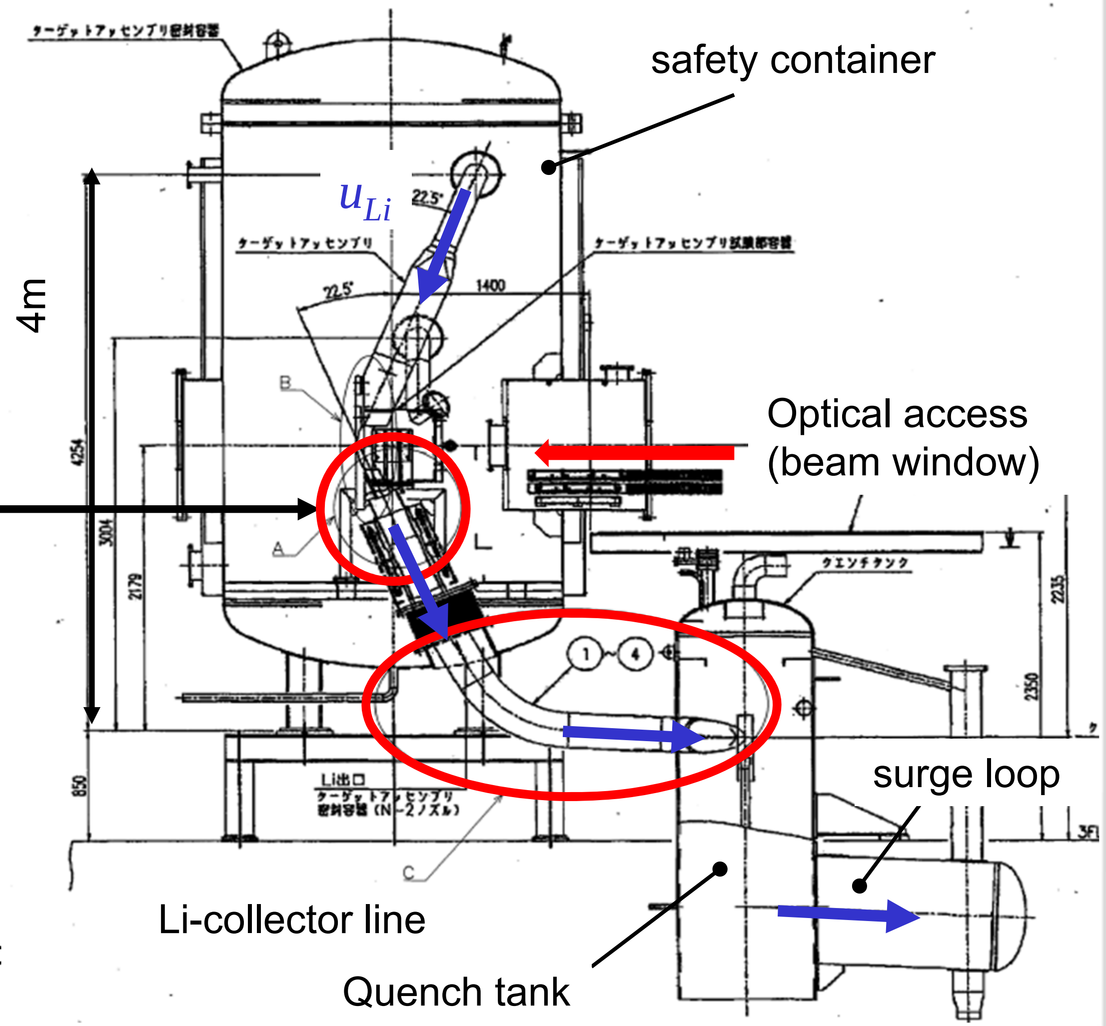
➡ **Erection of target test loop (ELTL) including all components at prototypical scale (1:3)**

Objectives ELTL

- demonstration of hydraulic stability of Li target jet
- Li purification system in bypass using traps (C, O_2, N_2).

Key parameters target

- Mean Li-velocity u_0 = 20m/s
- pressure beam line p = 10^{-3} Pa
- Li-surface width w = 100mm



Observation :

- At low pressures accoustic noise recording @ prototypical conditions

➡ **Cavitation ?** (although vapour pressure Li p_v=10^{-5}F

➡ **initiator for present study**

Acoustic measurements in ELTL 1(3)

Experimental set-up

- x-axis along pipe bottom
- origin (x=0) at welding line (WL)

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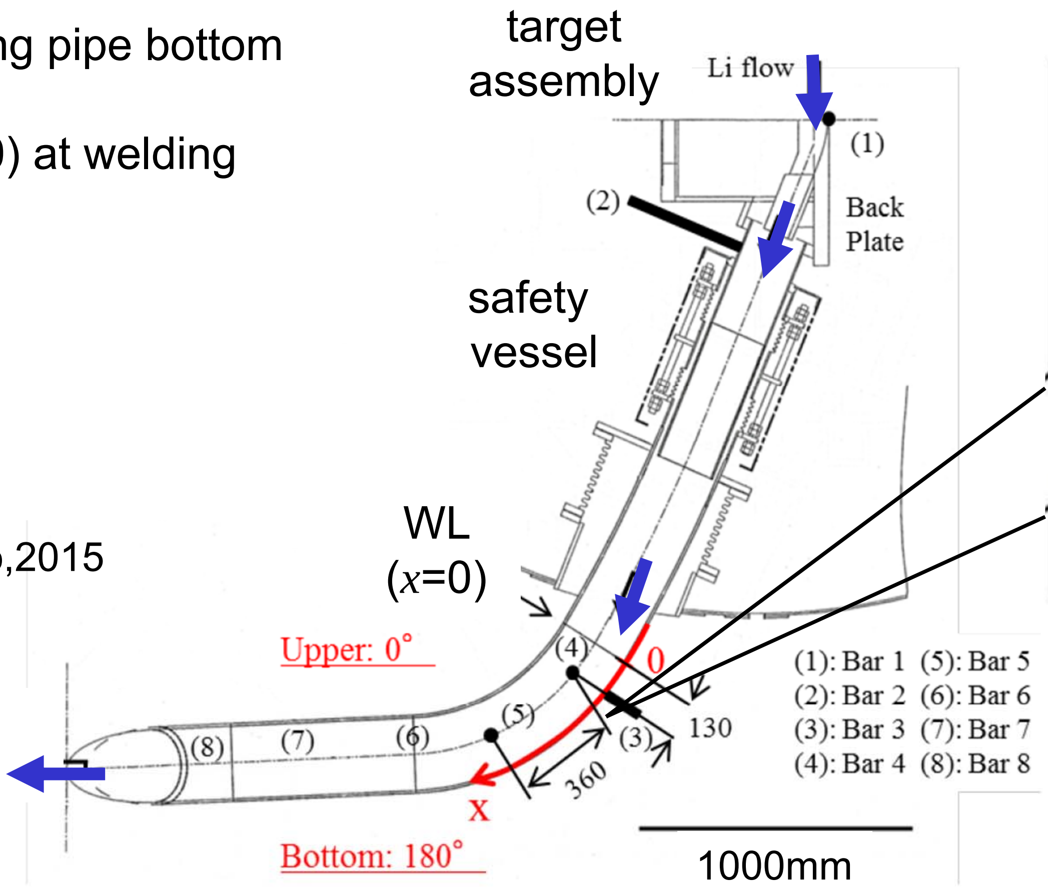
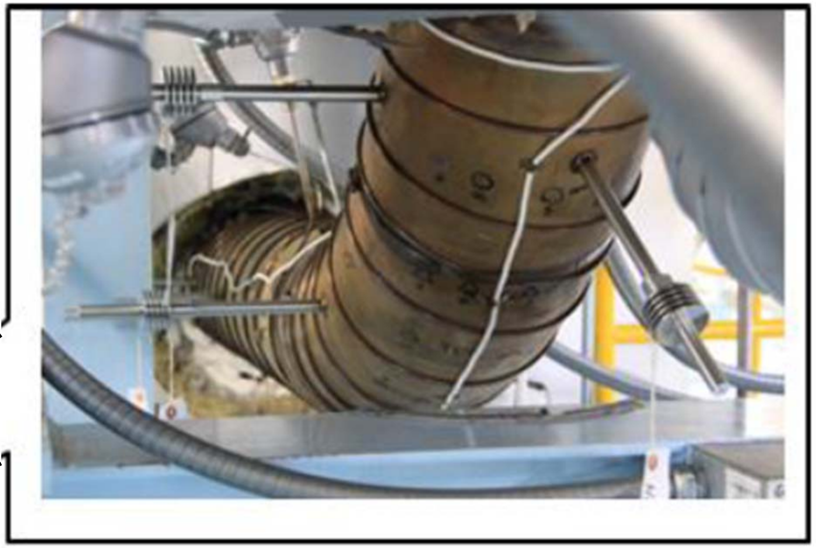
quench tank





Picture of the downstream pipe with the transmission bars. To be observed that transmission bars 3 and 4 are placed azimuthally in the same longitudinal position.

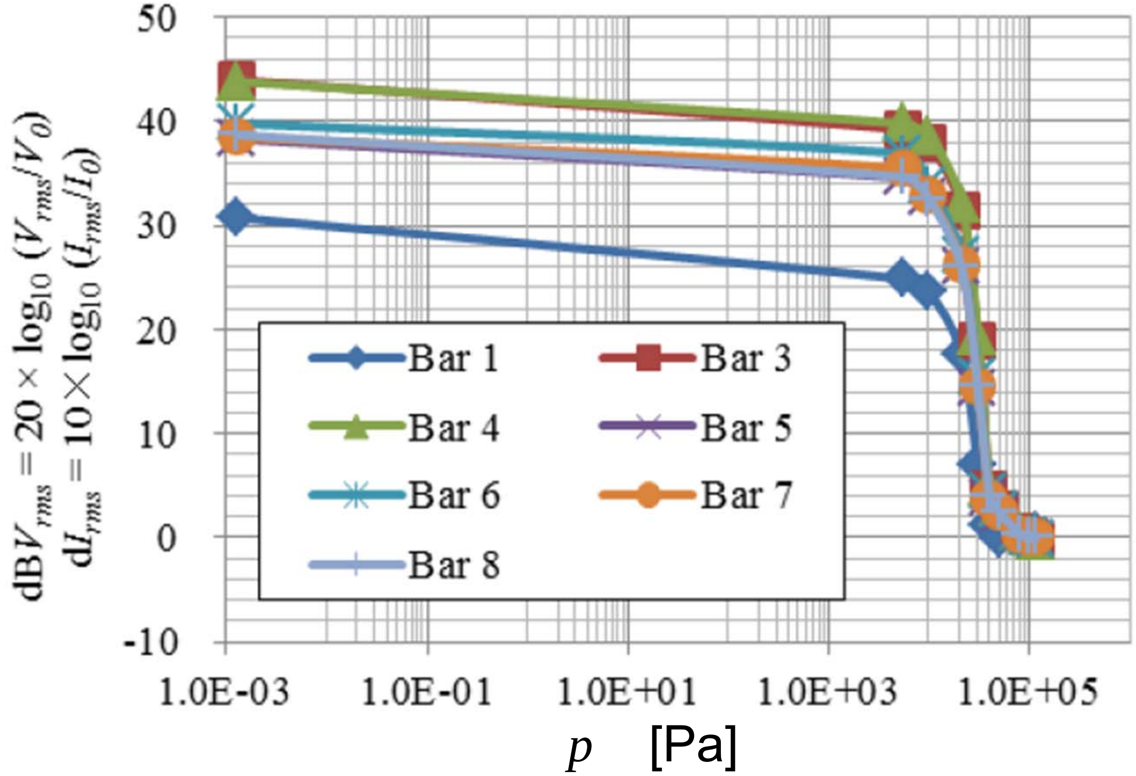
Equipment & matrix

- 8 acoustic emission (AE) sensors mounted on transmission bars along the downstream pipe.
- conventional loop instrumentation (Q, p)- monitoring
- test matrix (variation u_0, p)

(H. Kondo, notices @ VC meeting 11th March 2015)

Acoustic measurements in ELTL 2(3)

- measurement results (sound intensity vs. pressure, u_0=15m/s)



x-axis : Pressure

y-axis : RMS value of the AE sensor's voltage-signals (V_{rms}) are normalized by the RMS value at 100 kPa (V_0) in decibels.

- sound intensity rapidly increasing for p<30kPa
- sound intensity saturation for p<10kPa
- at $p=10^{-3}$Pa high intensities (≈45dB)

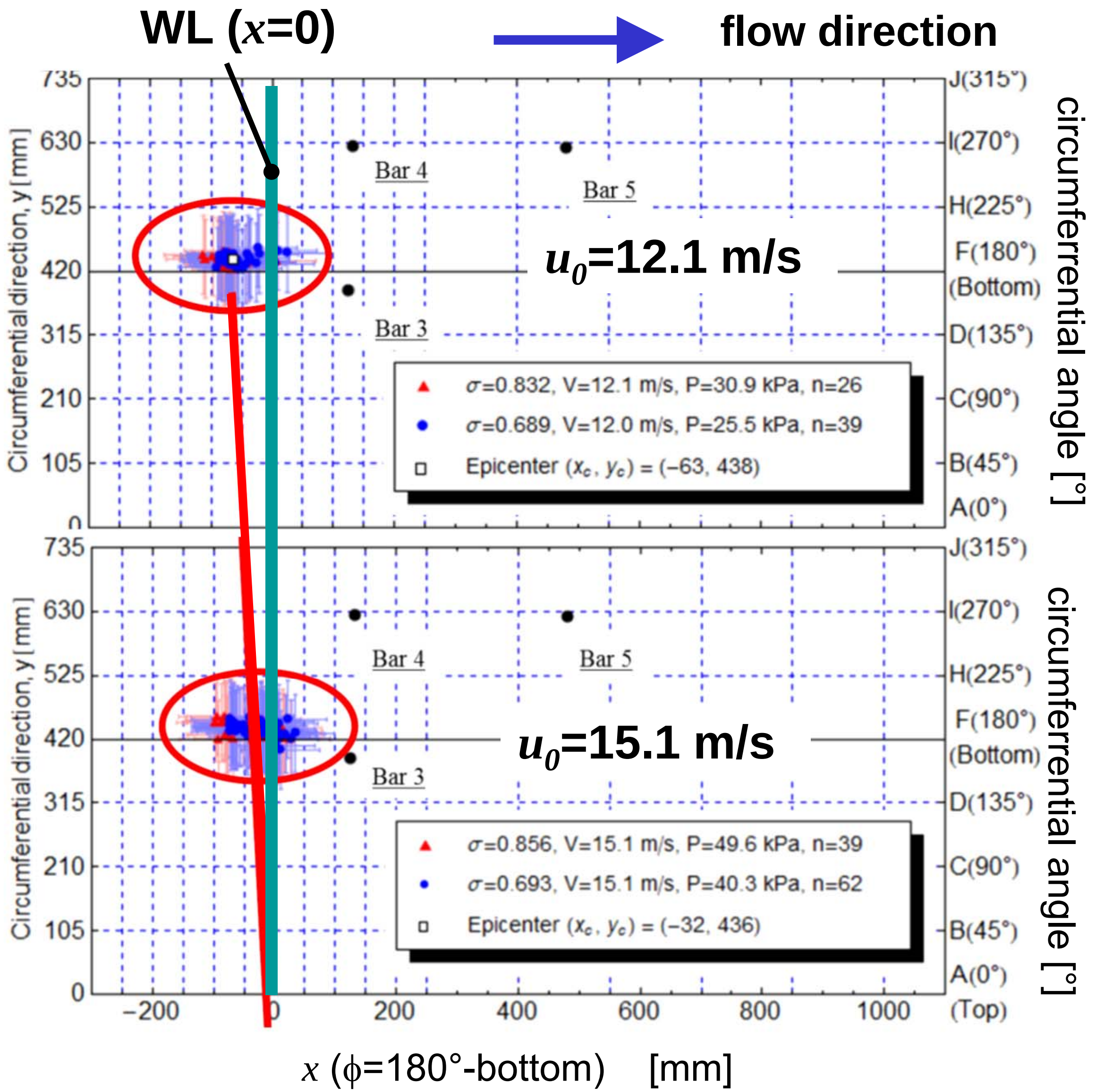
Phenomenon

- depends on pressure (CAVITATION=?)
- existence for threshold of onset

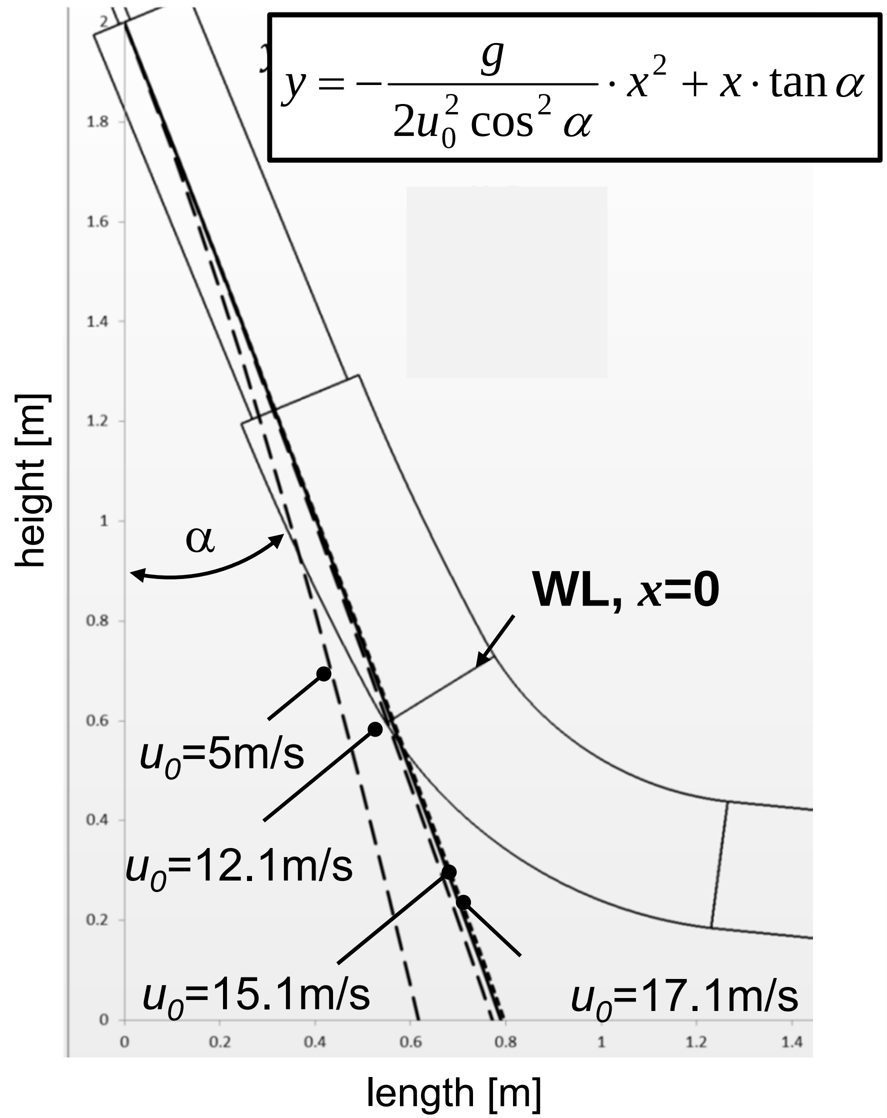
Where is the origin of the noise (location) ?

Acoustic measurements in ELTL 3(3)

- **Location of noise**



Jet trajectory motion



- shift of epicenter in x-direction for rising u_0

Numerical simulation- model description

Basis

- Multi-phase approach

Formulation

- Phase interaction control by means of Volume Of Fluid (VOF) technique
- Implementation of cavitation model (Li-liquid (l), Li-gas (g))
  - Seed-based mass transfer model
    n_0-density of seeds (10^{12} m^3),
    R-bubble radius ($5 \cdot 10^{-7}$m)

$$\alpha_g = \frac{V_g}{V_g + V_l} \qquad \alpha_g = \frac{4/3\pi\, n_0\, R^3}{1 + n_0\, 4/3\pi\, R^3}$$

➡ set to default values of water (absence of Li-data)

  - Inertia controlled cavitation bubble growth model (Rayleigh-Plasset equation)

$$\left(\frac{DR}{Dt}\right)^2 = \frac{2}{3}\left(\frac{p_{sat} - p_0}{\rho_l}\right)$$

p_{sat} -saturation pressure,
p_0 - pressure of the surrounding liquid,
ρ - liquid density

- VOF-free-surface model (Li-liquid (l)/ Ar-gas)
  - Surface tension modelled by continuum surface force (CSF) technique (super-position of normal and tangential force variation along interface)

$$f_\sigma = f_{\sigma,n} + f_{\sigma,t} \qquad f_{\sigma,n} = \sigma\, K\, n \qquad f_{\sigma,t} = \frac{\partial \sigma}{\partial t} t$$

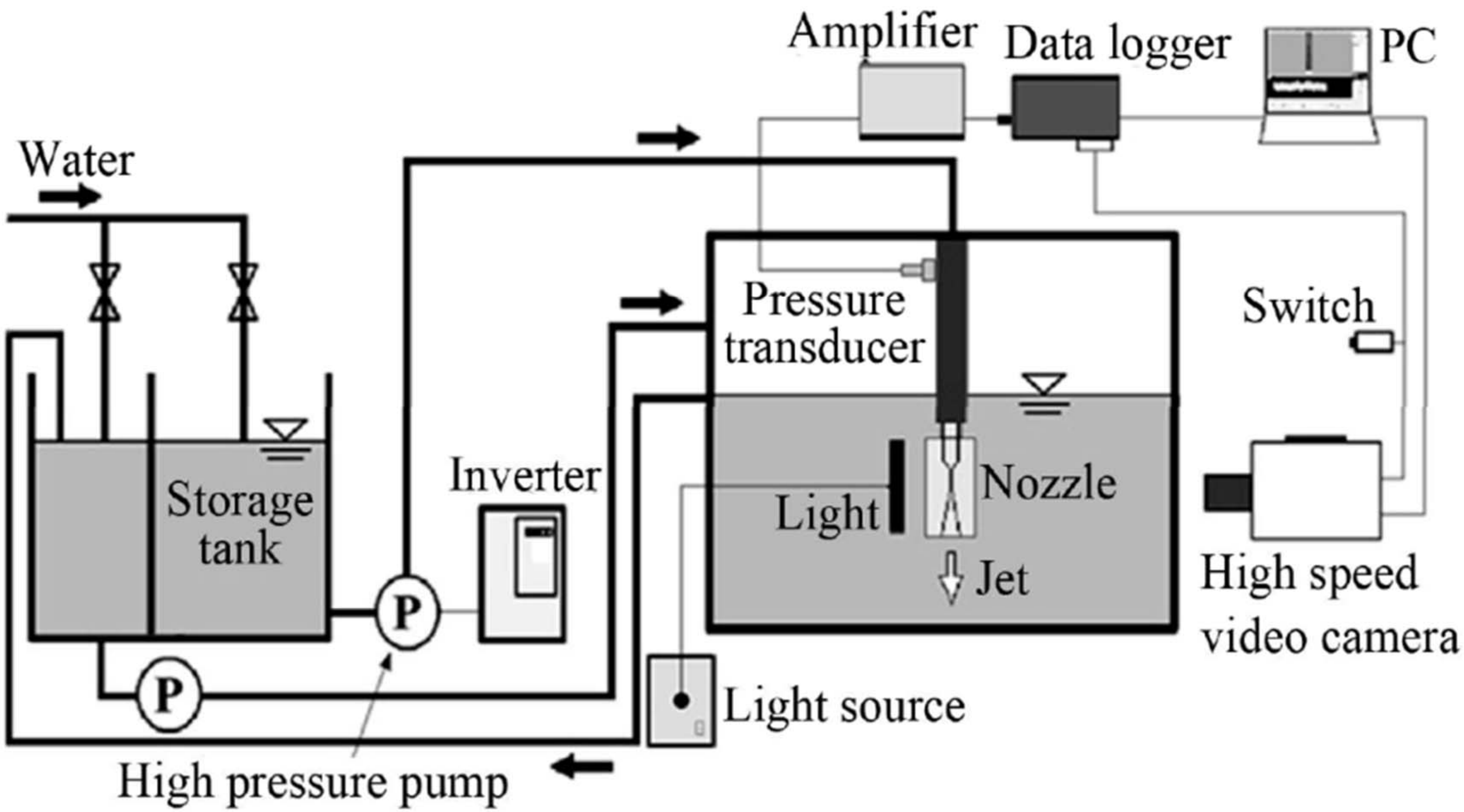
n / t – normal/tangential, unity vectors
σ - surface tension,
K - interface curvature,

- wall boundary conditions: capillary effects and contact angle
- gravity as volumetric force $f_g = g$

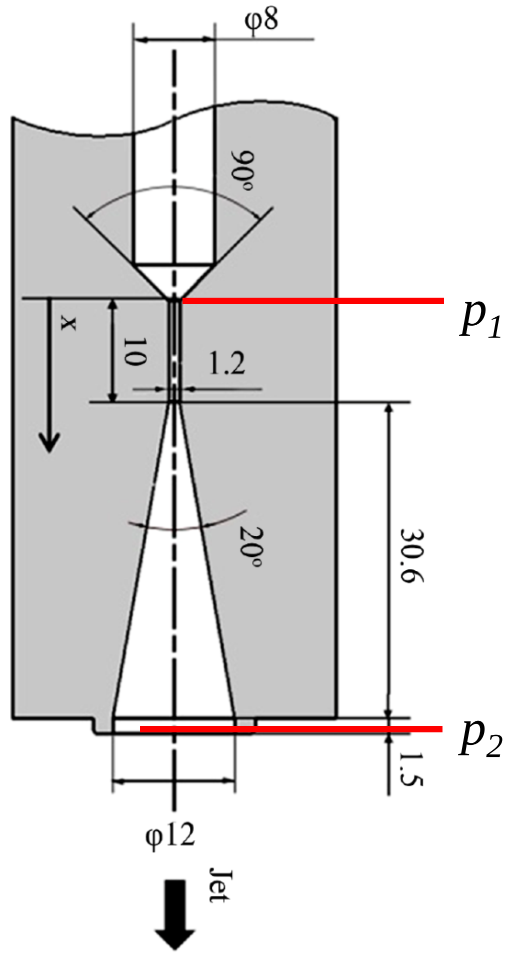
Numerical simulation- model validation

- model qualification by water experiment (literature)
- submerged water jet in water pool

  Expectation: $u_0 > u_{crit}$ ➡ cavitation in jet flow



Cavitation nozzle



Experimental conditions:

Ca=1.2, T_{water}=297K, dissolved oxygen β=5.5 mg/l

Keiichi Sato et al., High Speed Observation of Periodic Cavity Behavior in a Convergent-Divergent Nozzle for Cavitating Water Jet, J. of Flow Control, Meas. & Vis., 2013

Cavitation number Ca $$Ca = \frac{p - p_g}{1/2\left(\rho u_0^2\right)}$$

Numerical simulation- model validation

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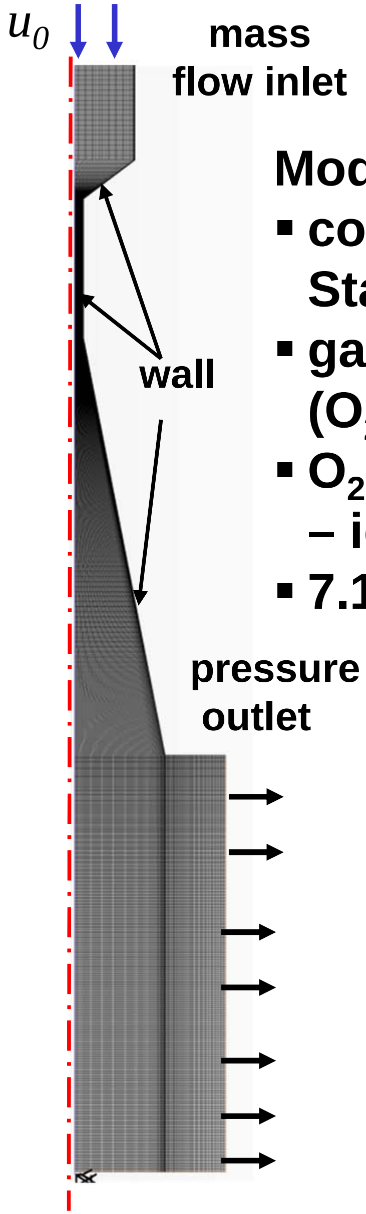
- geometry model



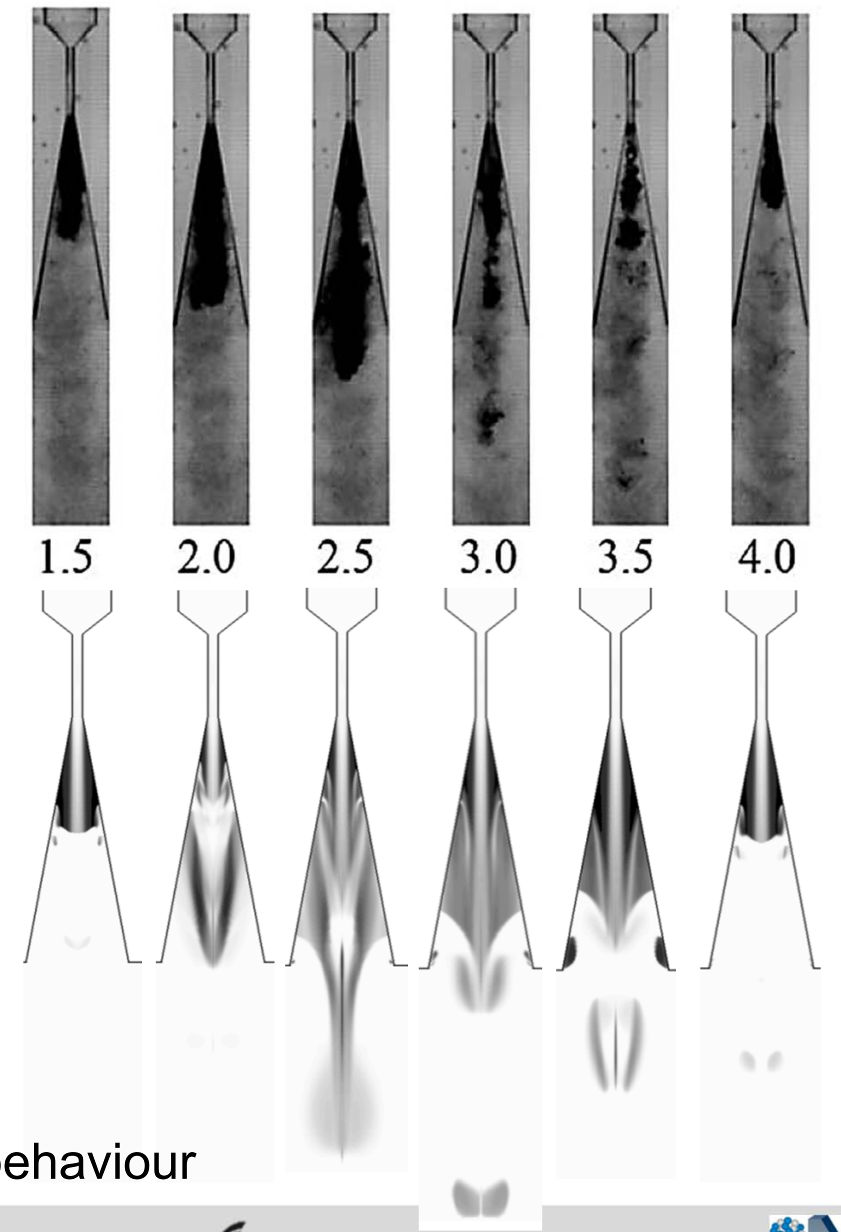
Modeling:
- **commercial Star-CCM+**
- **gas dissolution (O_2=5.5 mg/l)**
- **O_2 ,H_2O-vapour – ideal gas**
- **7.10^5cells**

- experimental observation
  - periodic behaviour of cavitation cloud in the nozzle

Exp.

black regions indicate cavitation clouds

time t [ms]



CFD

➡ agreement in shape and temporal behaviour

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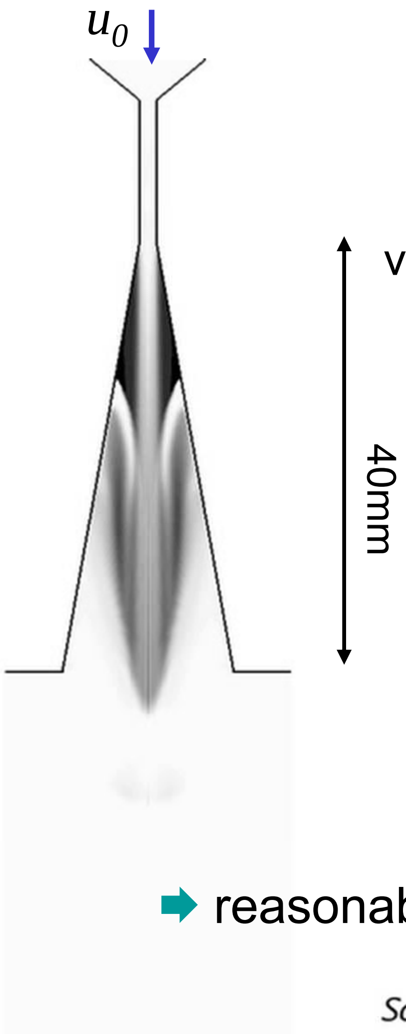
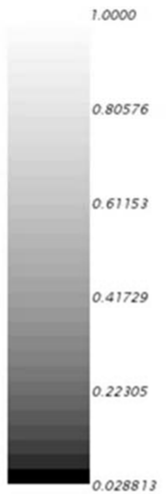
Numerical simulation- model validation

- Quantitative stochastic analysis
  - temporal progression (Sim.)



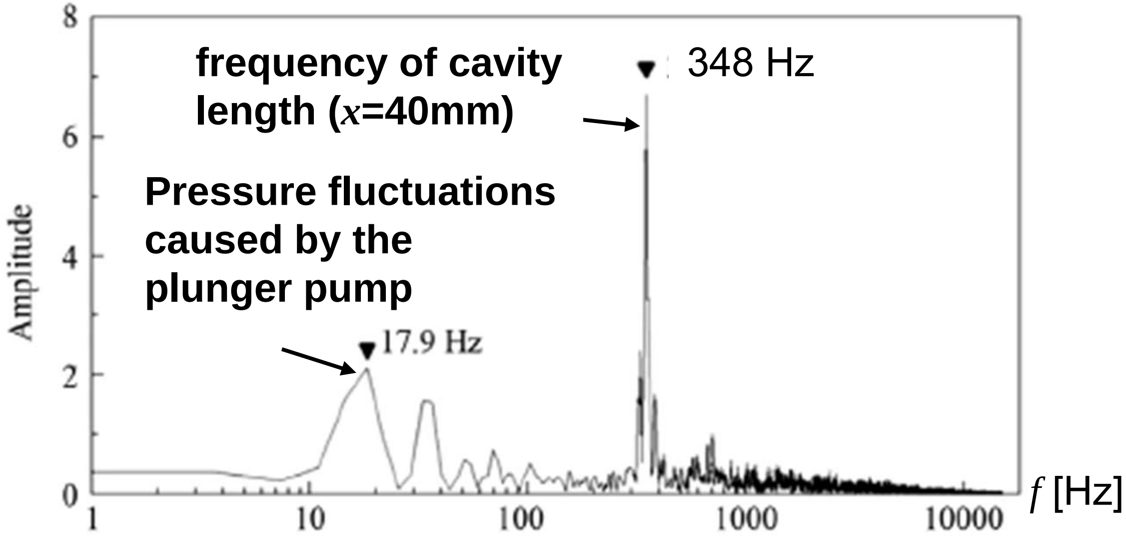


➡ reasonable cavitation model

Solution Time 0.2349 (s)

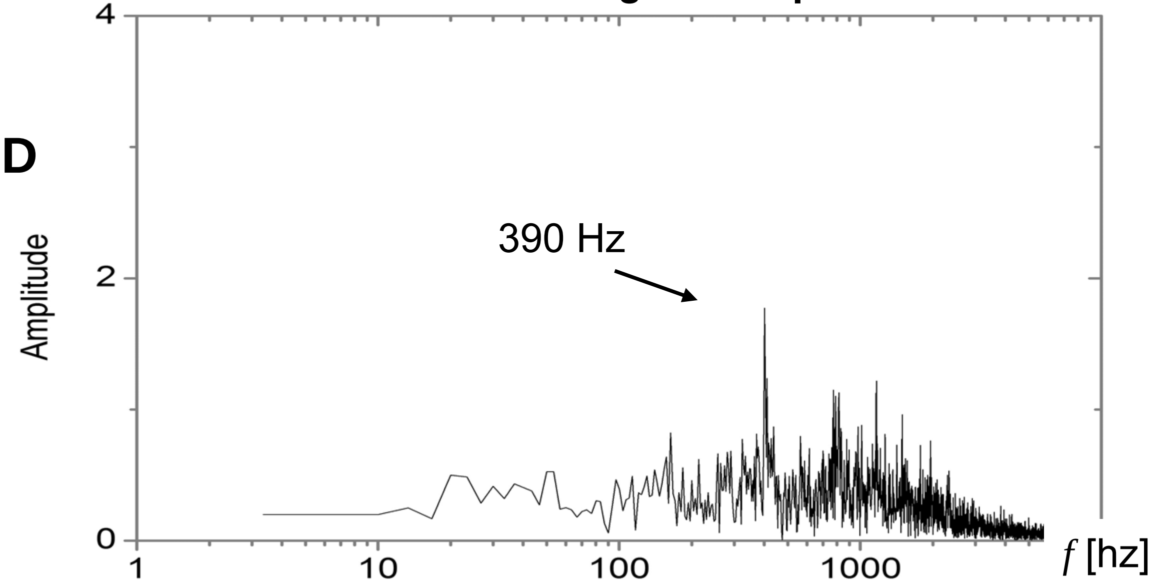
- FFT of gray level change in cavity length

Exp.



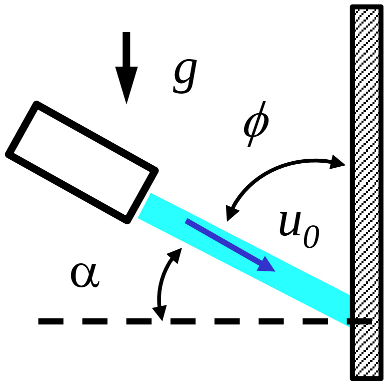
CFD

FFT analysis for calculated fluctuations of volume fraction of water gaseous phase



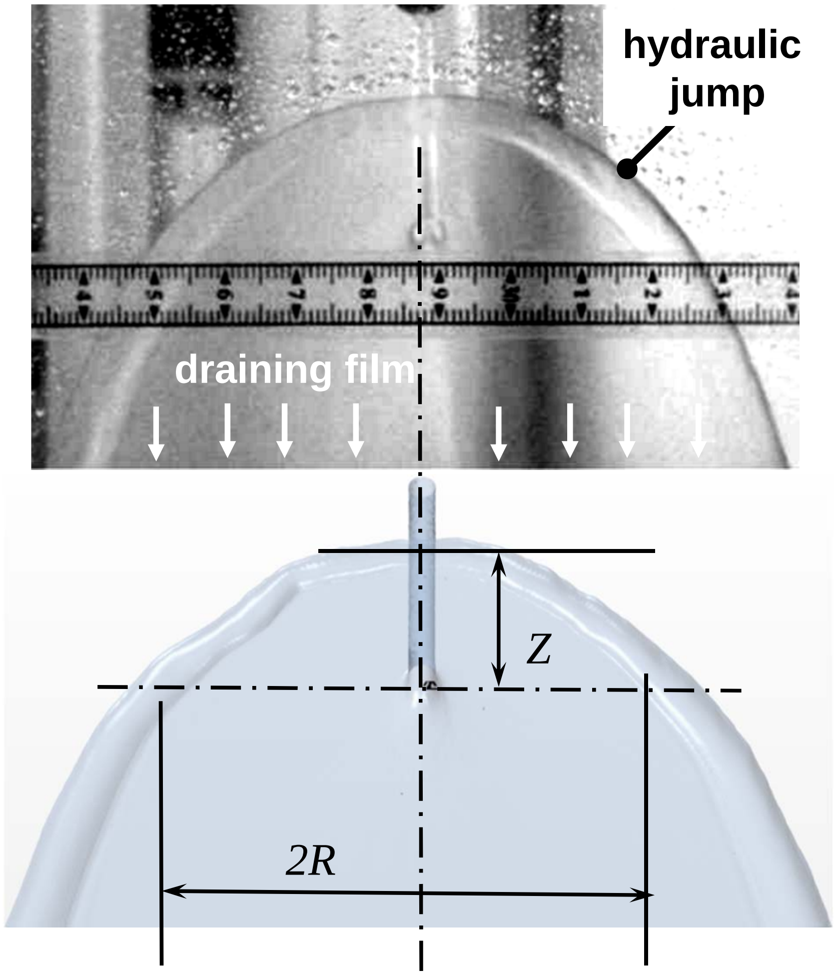
Numerical simulation- model validation

- qualification of gravitation, surface tension and contact angle model
- inclined water jet impinging on plane vertical plate (water/air) *



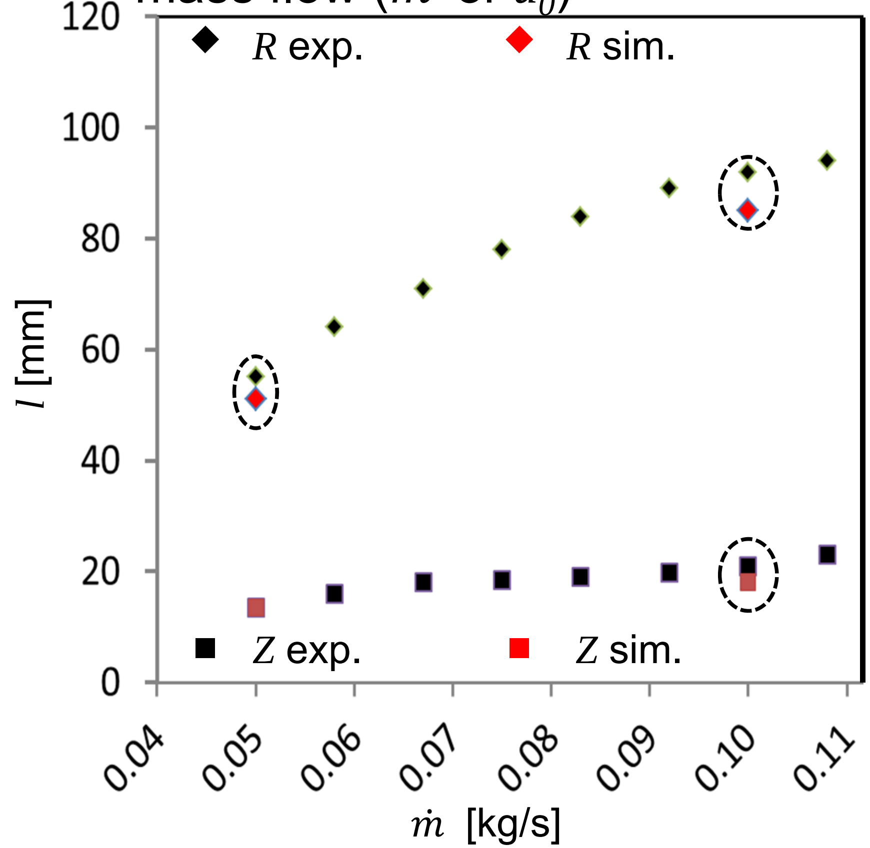
jet diameter d_i=3mm
α=45°,

- Film flow behind target (50 g/s)



➡ excellent shape agreement

- Film shape (Z,R) as function mass flow ($\dot{m}$ or u_0)

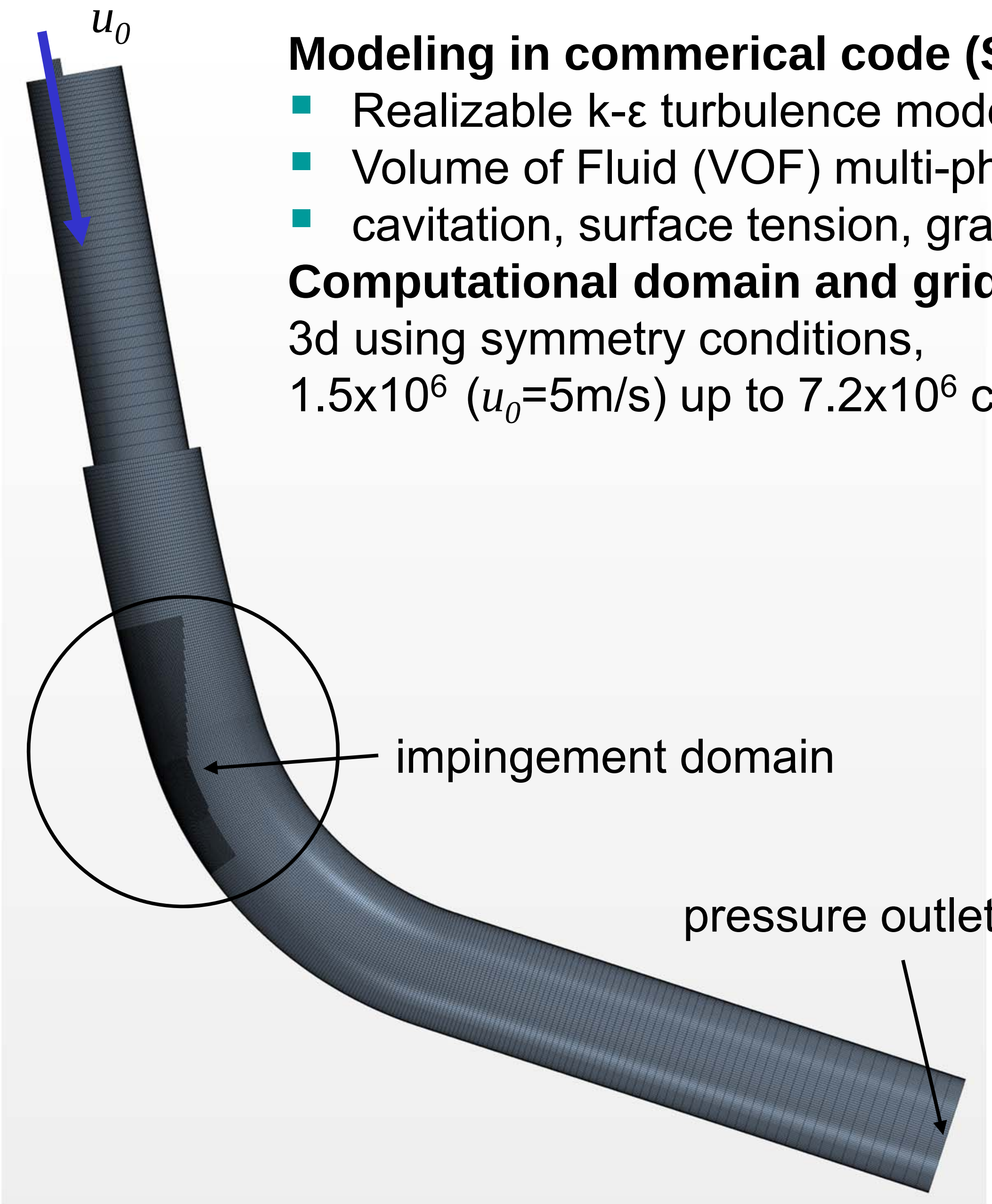


- perfect agreement in Z
- max. deviations 7% in R

➡ **model conceived to adequate to depict free surface with caviation**

*** T.Wang et al., Chemical Engineering Science 102 (2013)**

Numerical simulation - transfer to a Lithium jet



Modeling in commerical code (Star-CCM+)

- Realizable k-ε turbulence model
- Volume of Fluid (VOF) multi-phase model
- cavitation, surface tension, gravity

Computational domain and grid

3d using symmetry conditions,
1.5×10^6 (u_0=5m/s) up to 7.2×10^6 cells (u_0=15m/s)

Initial conditions:

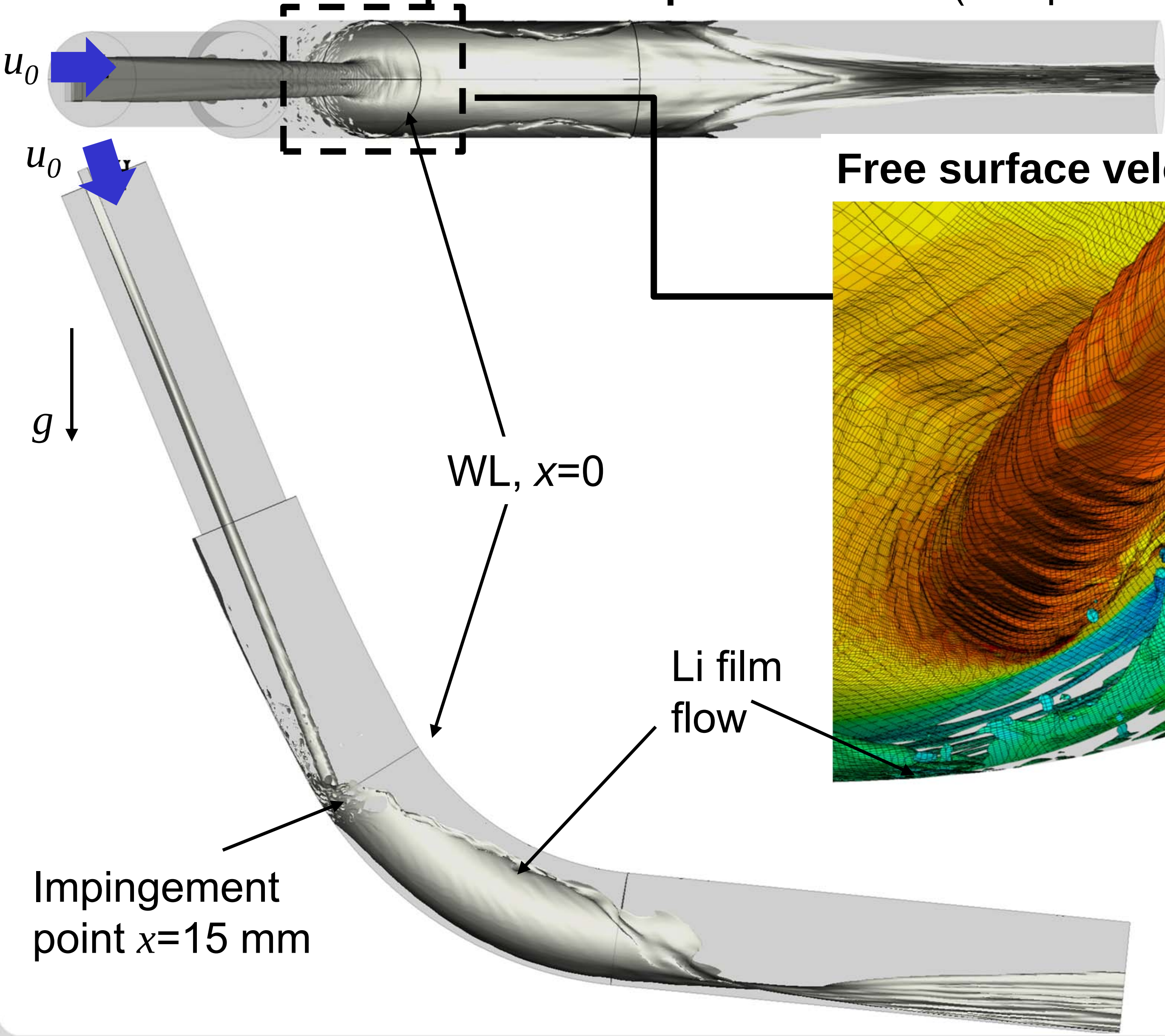
- u_0= 5, 15 m/s
- p_g= 10^3, 10^{-3} Pa
- ρ_{Li}=500kg/m^3≈const.
- σ_{Li}=0.41N/m
- Ar, Li vapour– ideal gas

Boundary conditions:

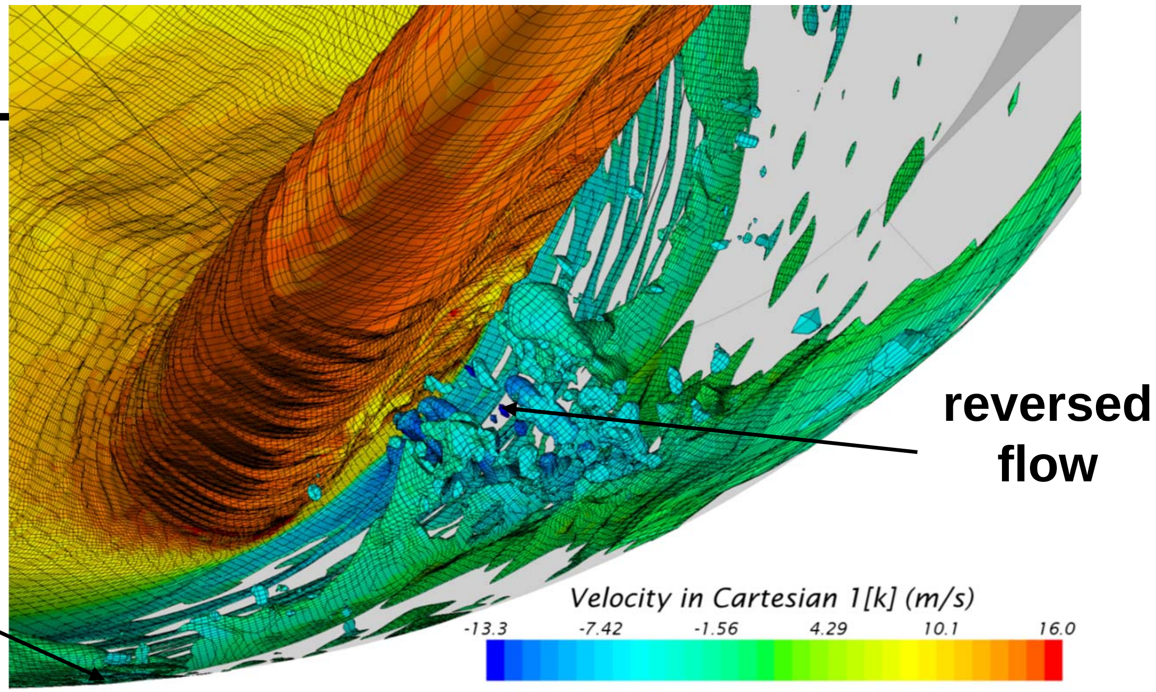
- $u|_{wall}$=0
- hydraulically smooth walls
- contact angle 60°
- $\Delta t=10^{-5}$s

Analysis –target flow (ref. operating conds. 1/4)

- **Conditions: u_0=15 m/s, p=10^{-3} Pa**
- **Iso-surface of liquid-lithium phase VF=0.7** (comp. time 1.5 s)



Free surface velocity in jet impinging region

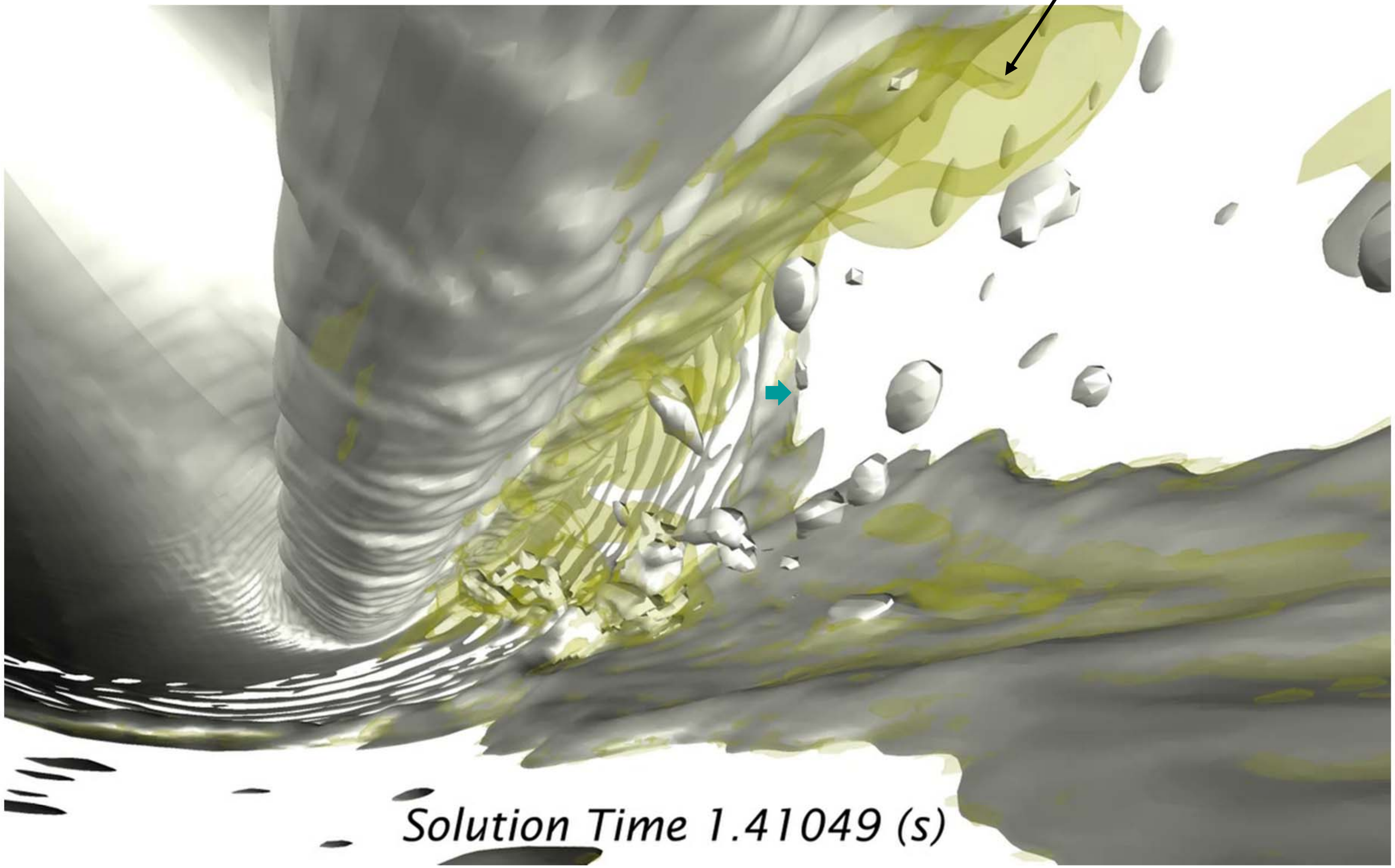


- momentum initiated upstream motion of droplets

Analysis –target flow (ref. operating conds. 2/4)

- Conditions: u_0=15 m/s, p=10^{-3} Pa
- Jet flow – Lithium$_{(l)}$ iso-surface VF=0.7

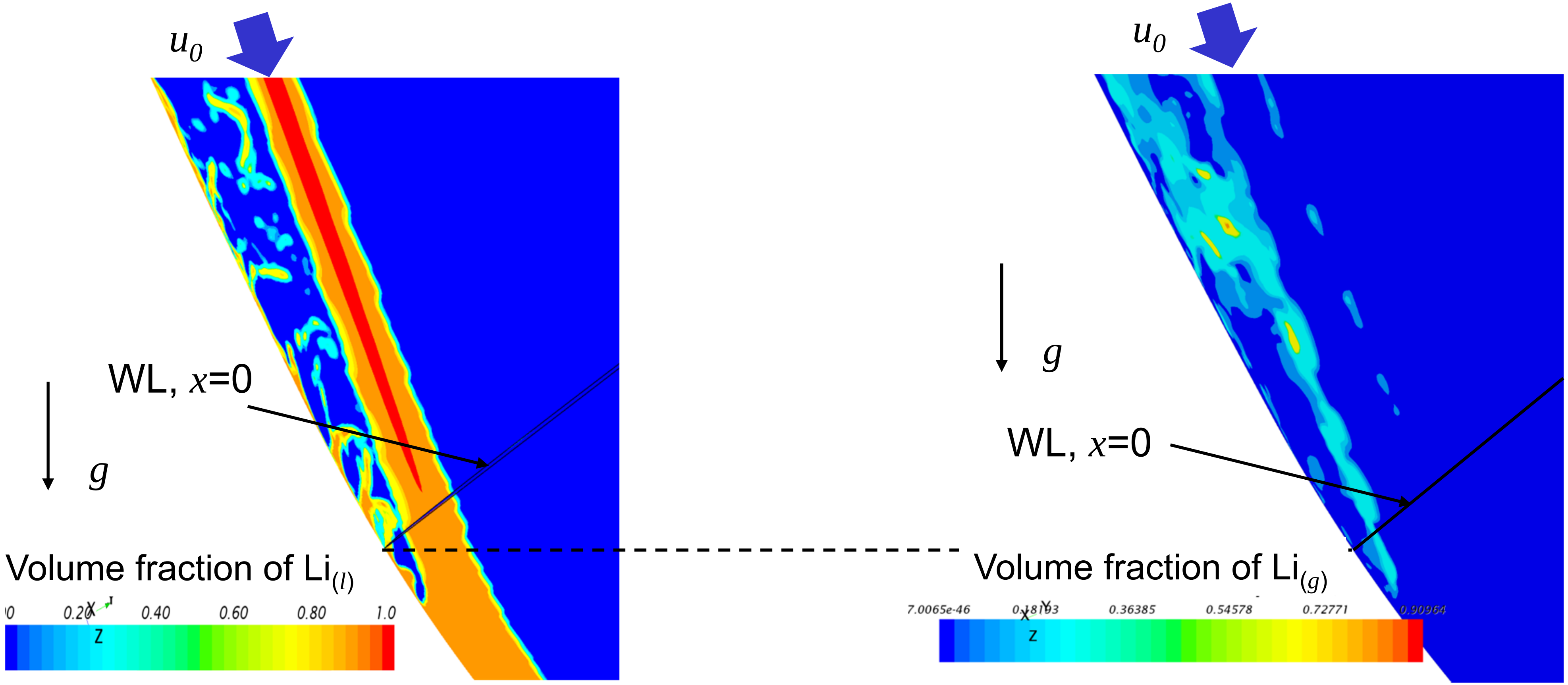
Lithium gas/liquid mixture iso-surface Li$_{(g)}$ 5%



➡ Lithium vapour mainly upstream impingement position

Analysis –target flow (ref. operating conds. 3/4)

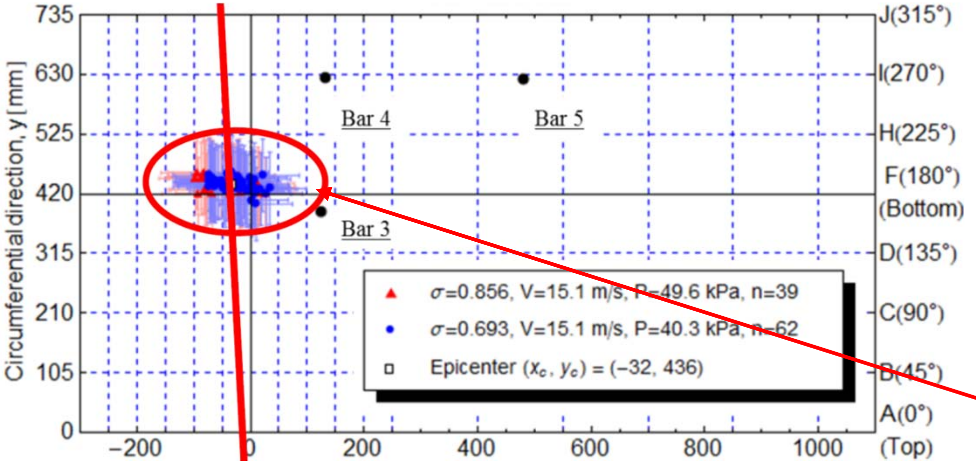
- Conditions: u_0=15 m/s, p=10^{-3} Pa
  - **Liquid Phase**
  - **Gas Phase**



Interaction of impinging jet with reversed flow
- **intense small scaled bubble generation**
- **mixing of liquid and gaseous Lithium**
- ➡ **ensuing transfer of gaseous lithium into the impinging area**
- ➡ **bubble collapse (cavitation)**

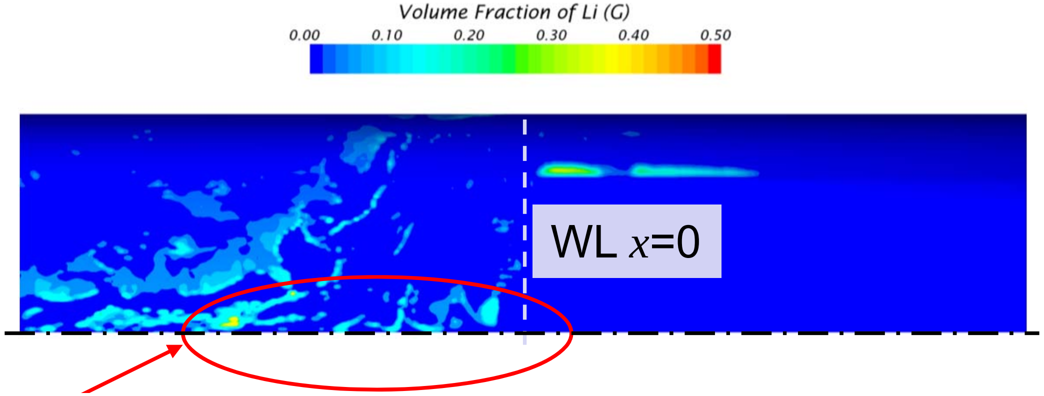
Analysis –target flow (ref. operating conds. 4/4)

- Conditions: u_0=15 m/s, p=10^{-3} Pa
- **Does observed location coincide with experimental observation ?**



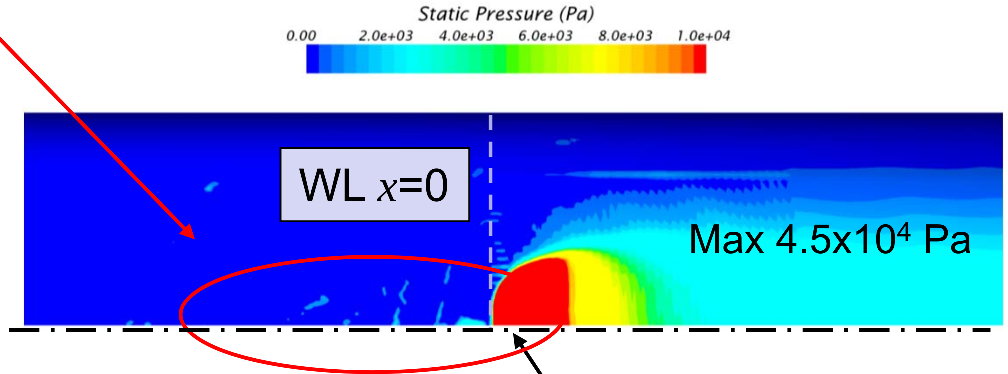
x (ϕ=180°-bottom) [mm]

- Volume fraction of $Li_{(g)}$ on the pipe wall



estimated location of AE

- **Static pressure on the pipe wall**



impingement point x=15 mm

Observation

- Measured length of AE area (100-120 mm) corresponds to area with high concentration of Li(g) on the pipe wall
- Deviation from measured position of AE epicenter and calculation is $\Delta x \approx$ 50 mm.

(H. Kondo, notices @ VC meeting 11th March 2015)

Analysis –target flow

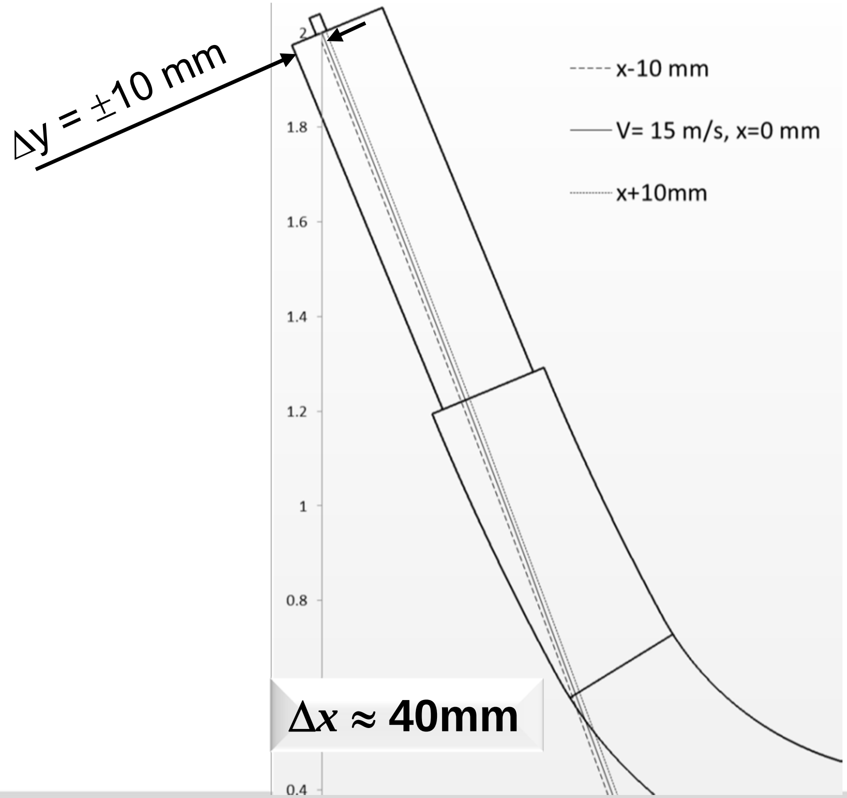
- Reasons for uncertainties in computed position of jet impingement position

Potential sources

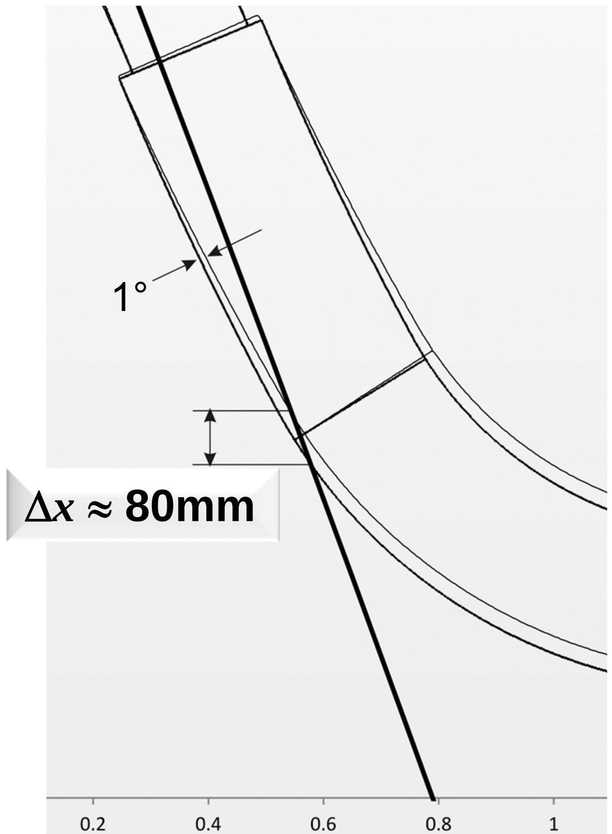
- miscellaneous flow reading ➡ initial velocity (±1m/s) ➡ $\Delta x \approx$ 7-8 mm
- Improper jet cross-section shape ➡ negl. impact due to momentum governed problem
- Mismatch exp. geometry ⇔ model ➡ large impact (!!!)

Manufacturing –mismatches: Examples

- Variation of normal distance y from the pipe wall to the jet inlet ±10mm

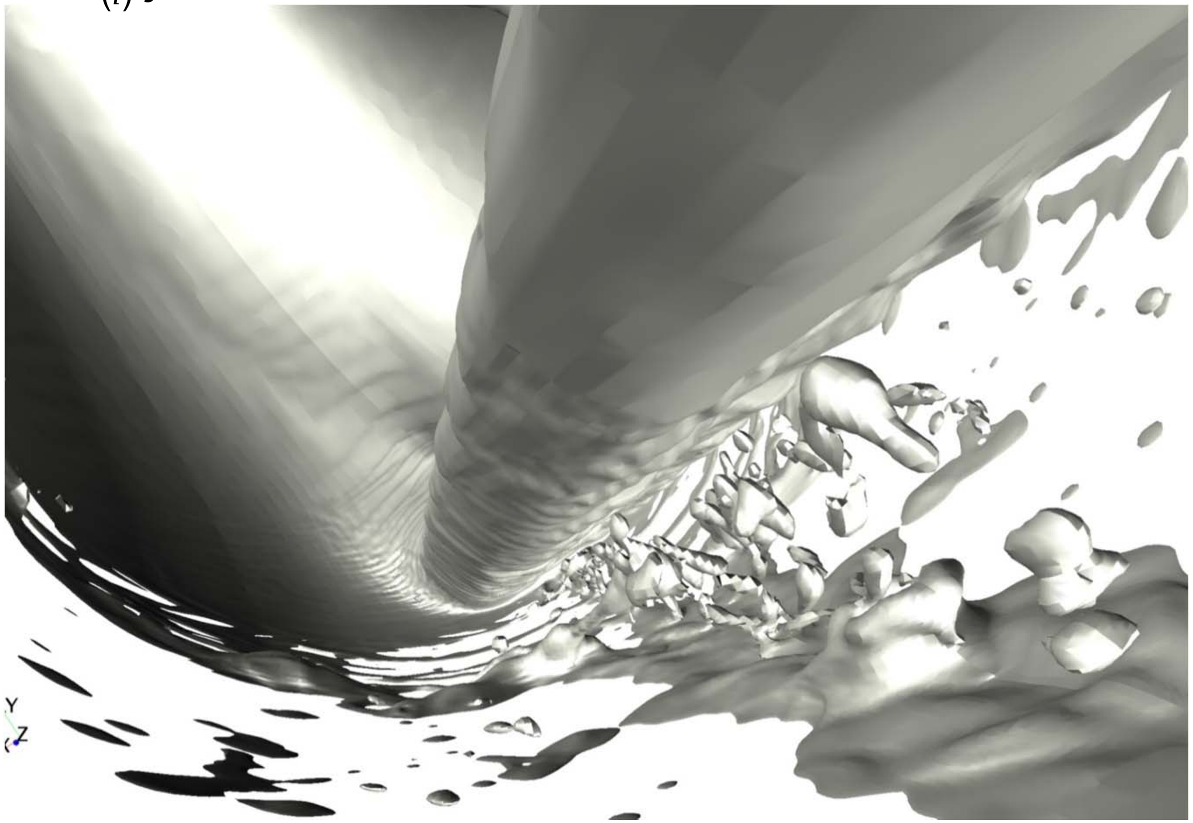


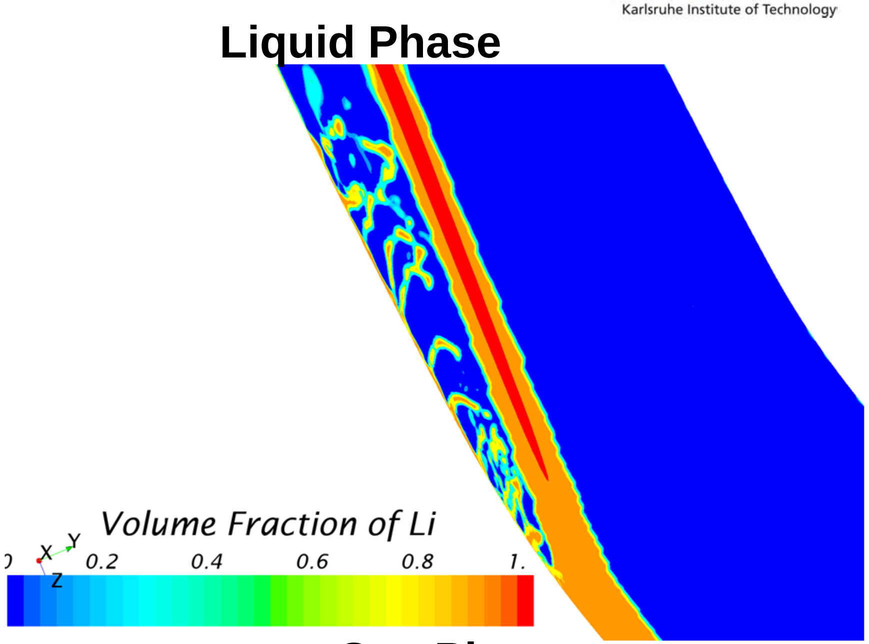
- 1° misalignment from pipe axis

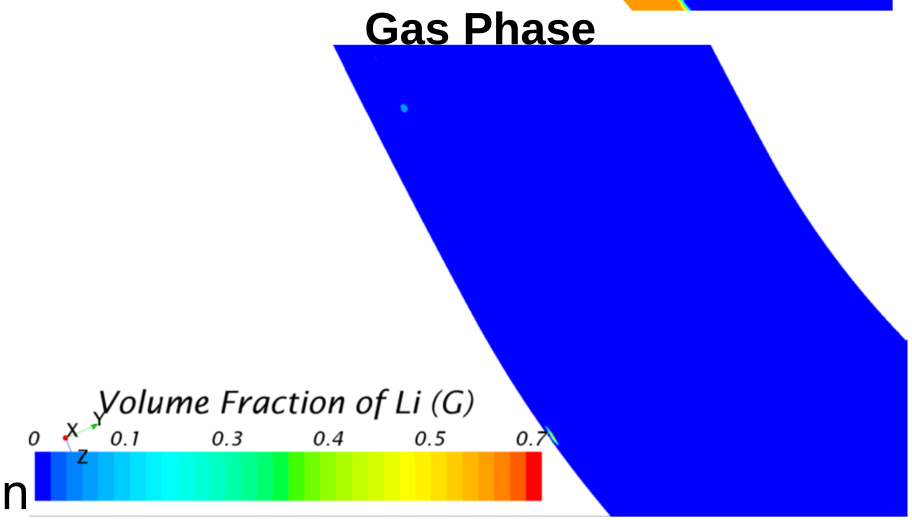


Analysis –target flow

- Conditions: u_0=15 m/s, p=10^3 Pa
- Li $_{(l)}$ jet iso-surface VOF=0.7







- absence of Li$_{(g)}$ fraction (experiment @ p=30kPa)

Potential sources

- dependence of cavitation model on the mesh resolution
- absence of reliable data on bubble seed density, initial bubble radius for alkali metals
- gases dissolved in the experiment ???

Conclusions &Ooutlook

- No occurrence of cavitation in Li jet bulk during at nominal conditions at nominal conditions in simulation (10^{-3} Pa, 15 m/s).

- wall impingement ➡partial backward flow ➡ droplet formation ➡ free surface increase
  ➡ Li vapor production, enough to lead to significant vapor fraction amount.
  ➡ Li vapor captured and reintroduced in the main flow.
  ➡ recovery of static pressure by transport ➡ bubble collapse ➡ cavitation

- Epicenter of cavitation can be predicted with accuracy of 50 mm. Deviations to experiment can be attributed to several sources (mainly geometric imperfections)

- Exp. observed cavitation even at 30 kPa and u_0= 15 m/s cannot be depicted numerically
  ➡ numerical sensitivity study underway , but likely
  ➡ modeling parameters (seed properties, scaling of bubble growth rate) requires complementary model experiments.