Cavitation and multi-phase phenomena in liquid rocket engine systems

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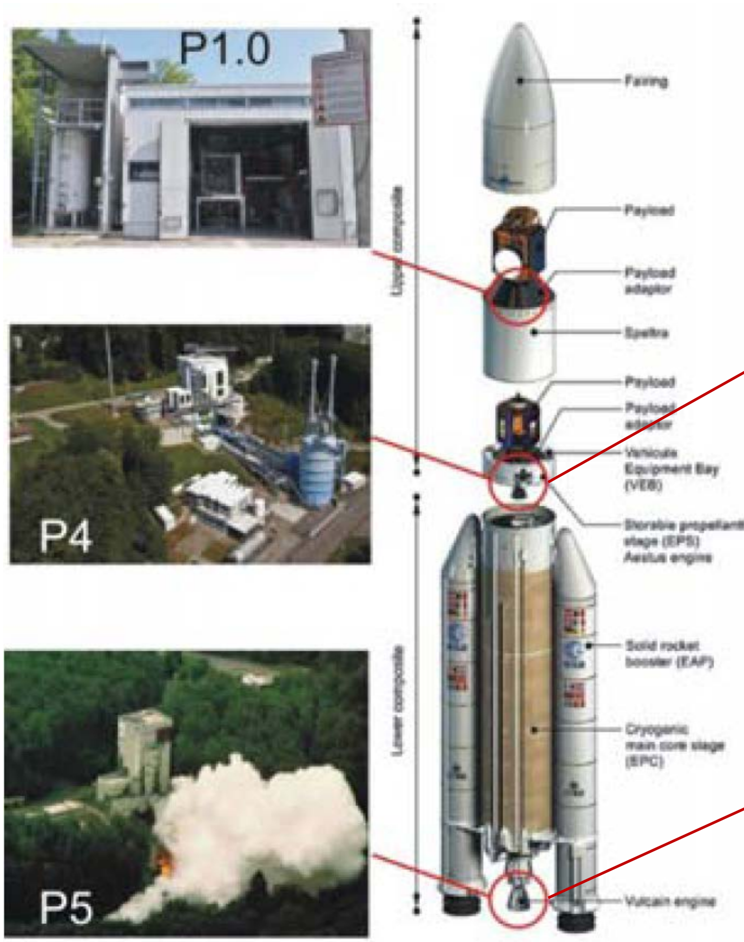


Aestus Engine, 30 kN
storable hypergolic propellants,
N2O4/MMH

Vulcain Engine, 1360 kN
cryogenic propellants,
LOX/LH2

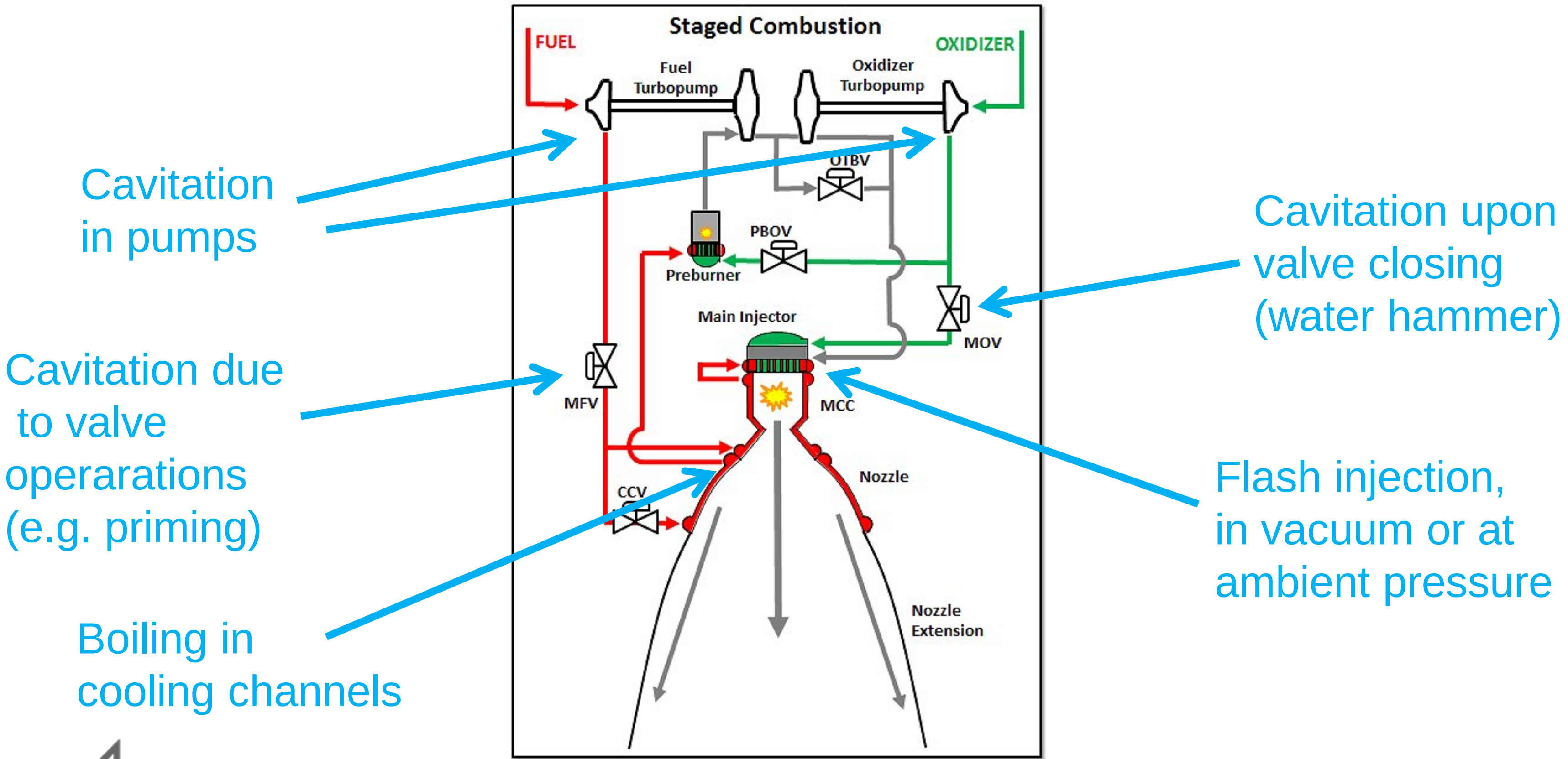
Outline

- Overview of cavitation events in LRE
  - Turbopumps
  - Flash injection
  - Valves operation
- Test cases:
  - Cavitation during water hammer
  - Priming
  - Numerical modeling

Introduction: Liquid Rocket Engines (LRE)

A LRE is a complex fluid network in which each propellant must be delivered from the tank to the combustion chamber.

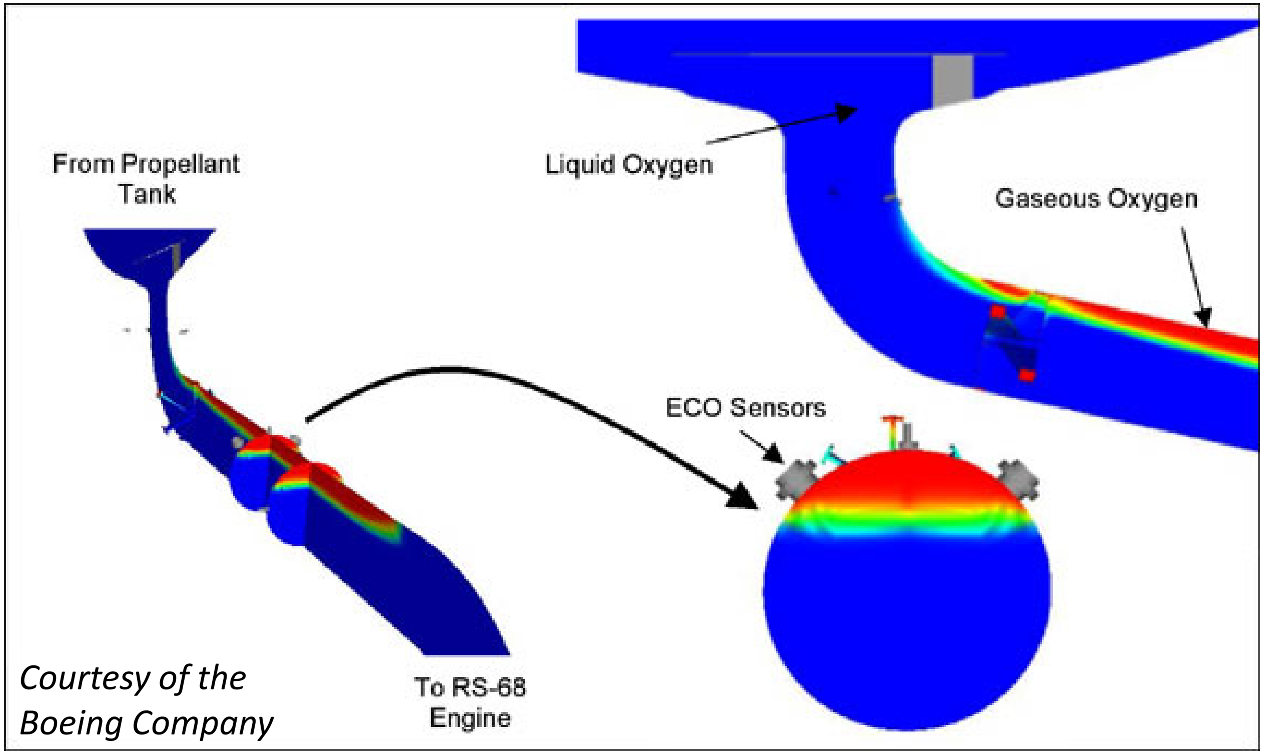
Cryogenic propellants are stored near their saturation point => cavitation is likely to occur



Real example of (expensive) cavitation: Delta IV Heavy

On 21 Dec 2004, cavitation in the LOX feedline caused a premature shutdown of the engine:

a pocket of gaseous oxygen formed and reached the Engine Cut-Off (ECO) sensor. This caused the ECO sensors to momentarily indicate dry, initiating then the shutdown sequence 8 sec earlier



Courtesy of the Boeing Company

Mission was a partial failure, since the payload was placed in a lower orbit ($$!)

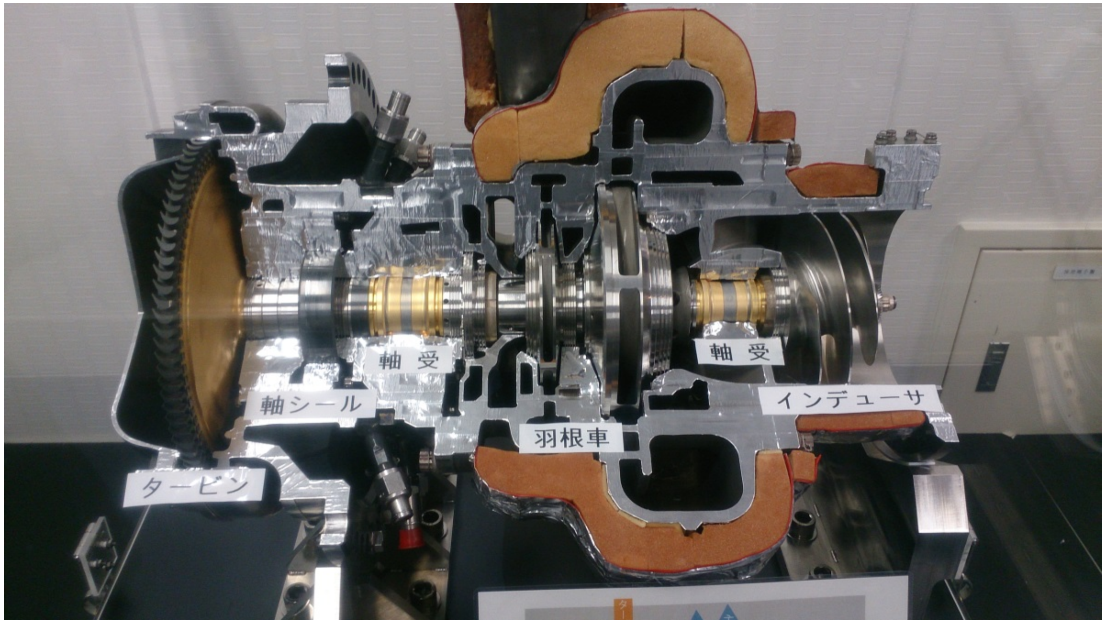
Cavitation in Turbopumps

Turbopump are key-components in LRE

	LH2-Pump [rpm]	LOX-Pump
Vinci	90000	18000
Vulcain 2	36070	12300
LE-7A (Japan)	42000	18300

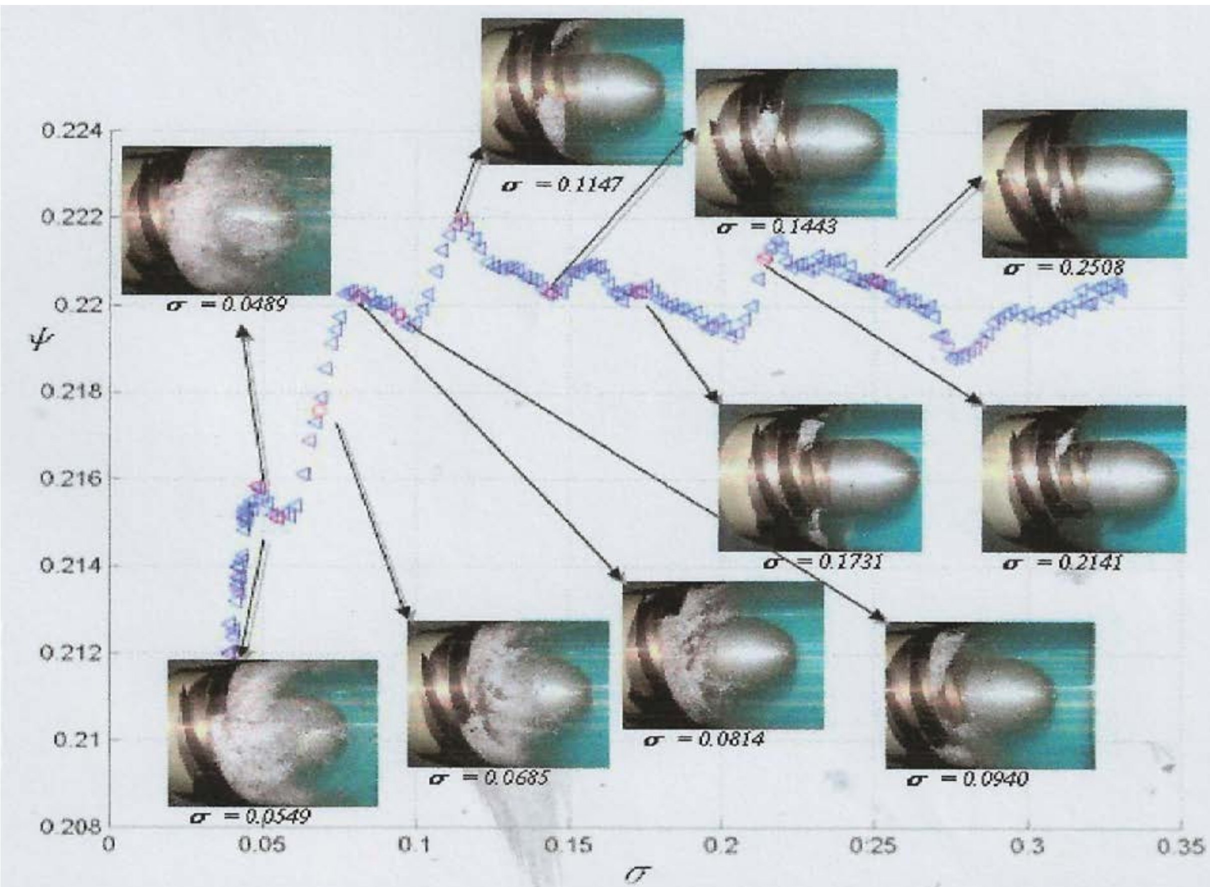
<u>Challenges:</u>

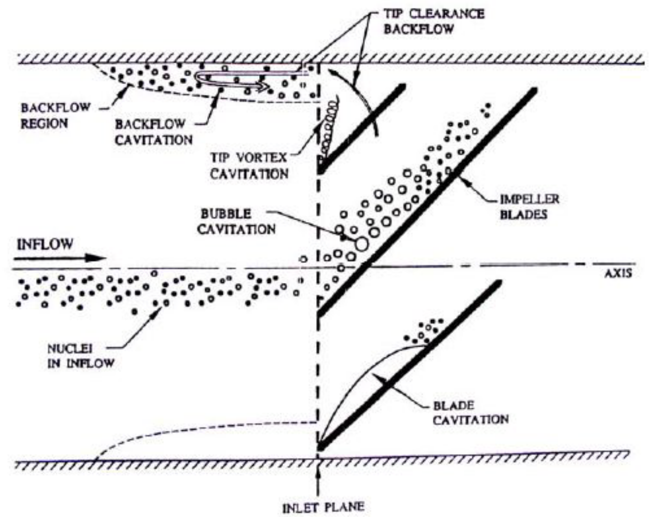
- High pressure ratios
  - 5 to 130bar in single stage pump (Vulcain 2)
- Weight
  - High rotational speed
  - Low available NPSH (tank mass)
- Power density
  - 14.25MW (LH2 Vulcain2)
  - ~70x40x40cm
- Reactive Fluids
  - LOx fire hazard

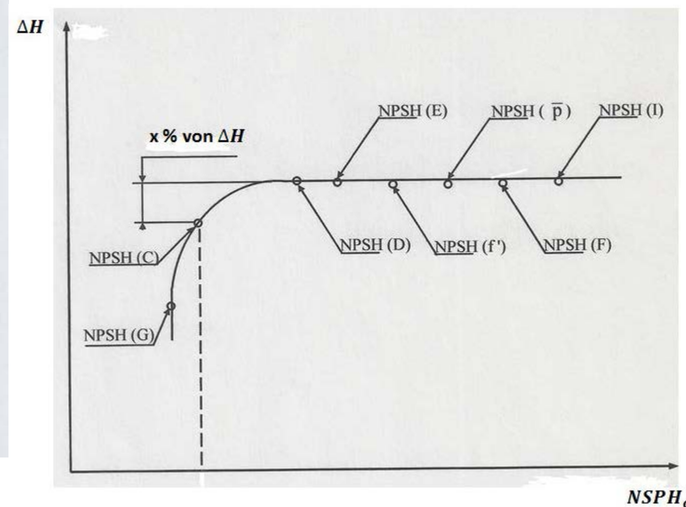


LE-7A LOx-Turbopump

Cavitation at the inducer

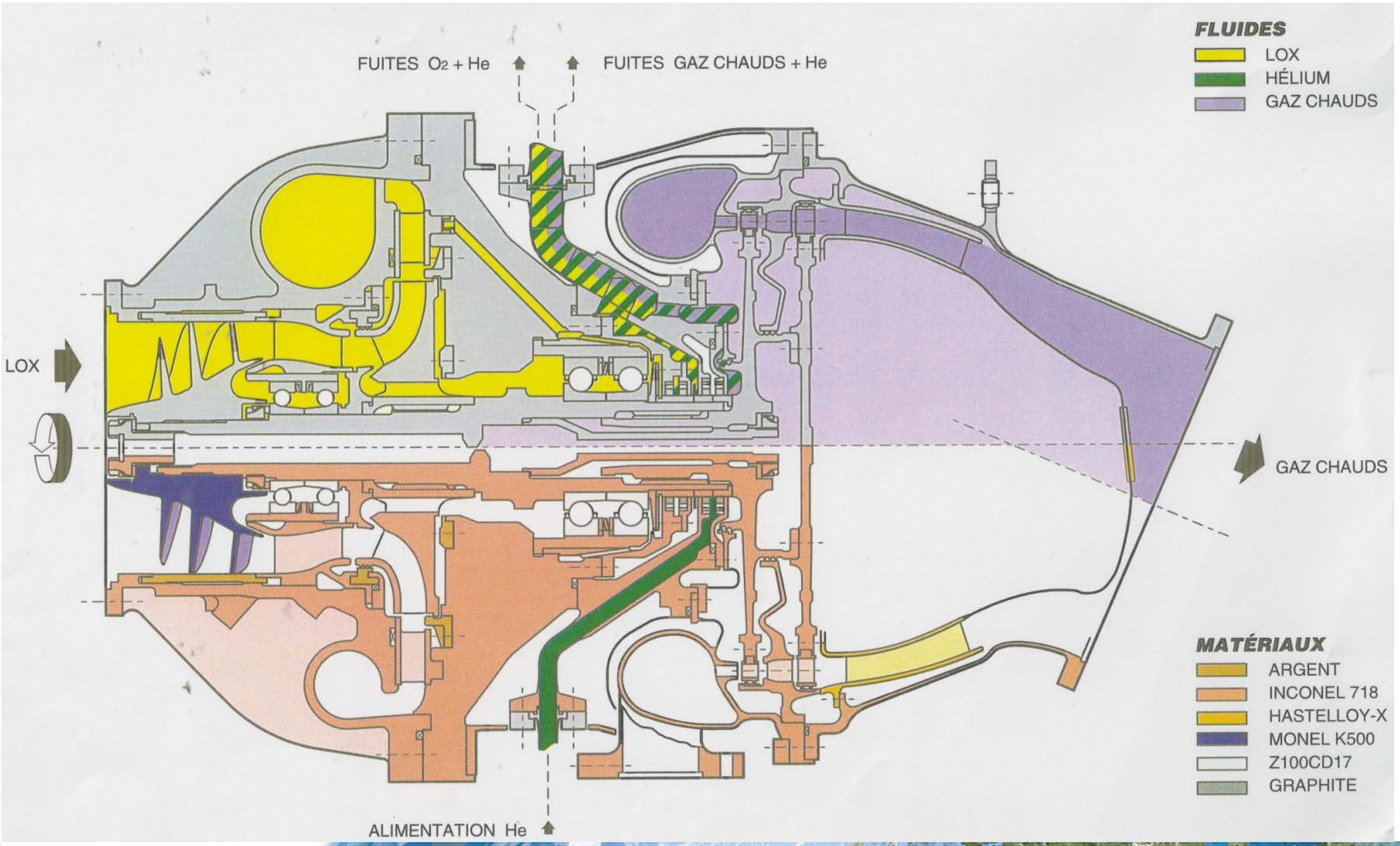




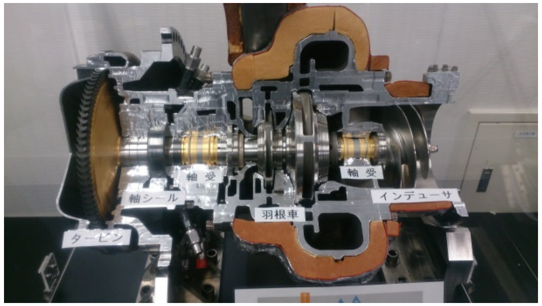


Cavitation Induced Vibration – LOx Turbopump

Fire hazard in case of LOX



Cavitation Induced Vibration: also difficult in LH2

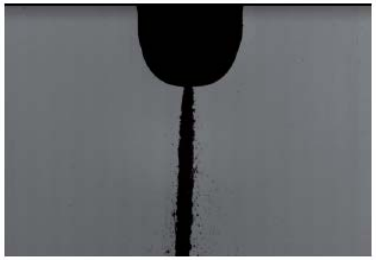


Flashing: state of research

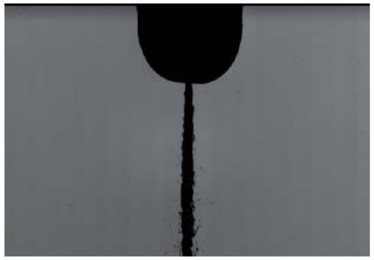
$$R_\mathrm{p} = \frac{p_\mathrm{sat}(T_\mathrm{inj})}{p_\mathrm{c}}$$

Flashing investigations

- with liquid hydrocarbons → Flash evaporation in jet dominated bubble nucleation; angle of spray as a function of pressure ratio and surface tension



R_p=0.949

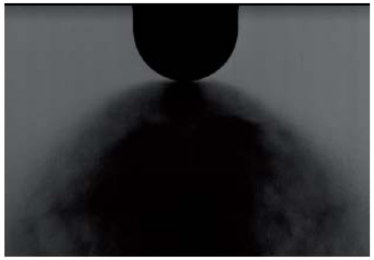


R_p=1.298

DLR-Lampoldshausen:

- observation of flash evaporation during studies of transient ignition processes with LOX injection into vacuum

R_p=2.310



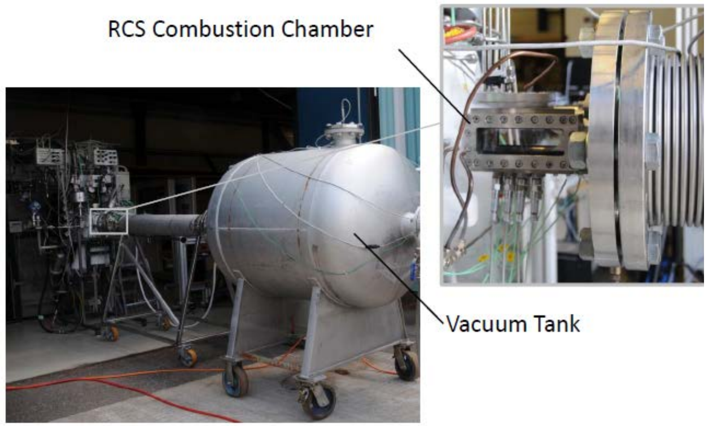
R_p=37.980

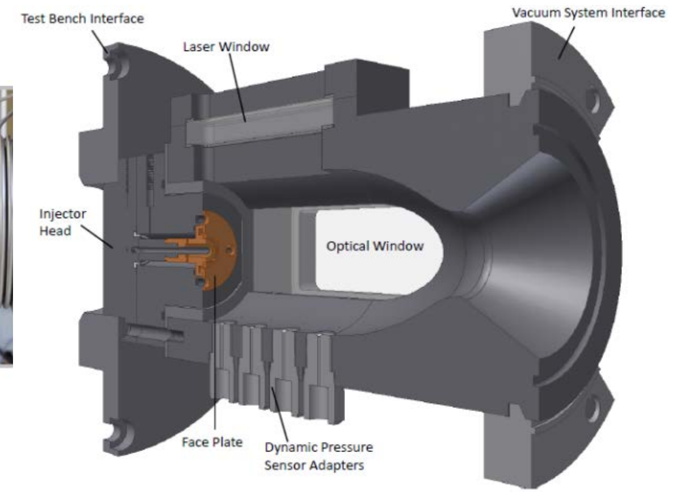
Cryogenic propellants (e.g. fuel LH2, CH4) might be already at supercritical conditions before injection

	P critical	T critical
LH2	13 bar	33 K
CH4	46 bar	190 K

Flashing experiment at DLR M3.1

- Test bench M3.1:
  - 400N experimental thrust chamber with vacuum system
  - 2 configurations
  - High-Speed Shadowgraph imaging
  - Injection temperature T_{inj} not adjustable

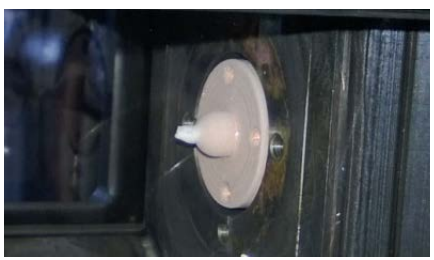




	Injector diameter D_{inj} [mm]	Injection pressure p_{inj} [MPa]	Injection temperature T_{inj} [K]	Back pressure p_c [MPa]	L/D [-]
config. #1:	2,4	0,25	94	0,0035-0,03	21,9
config. #2:	0,3	1,7	113	0,0035-0,03	1,2

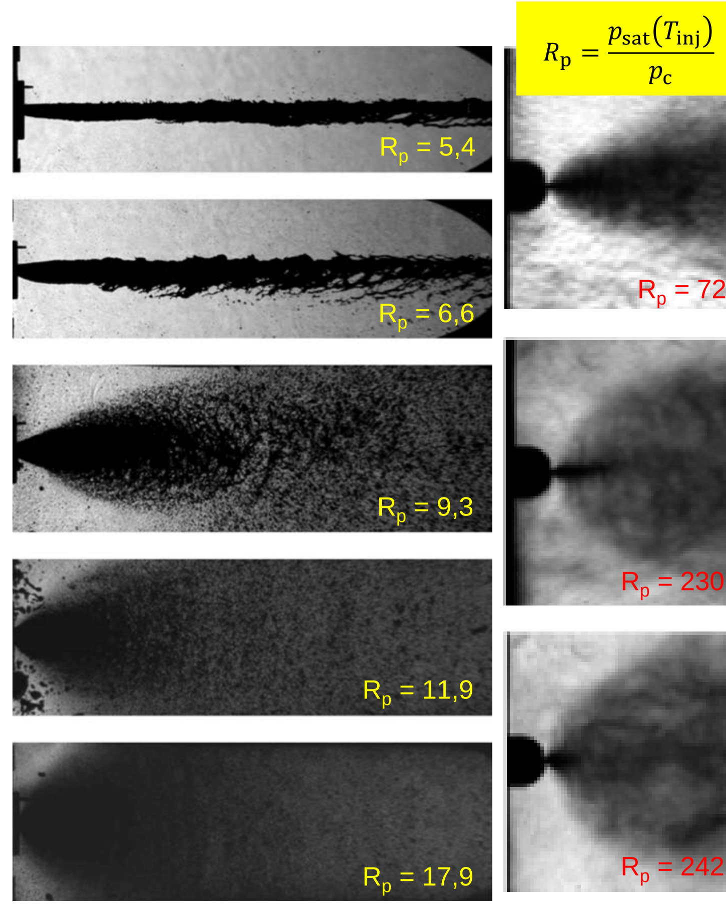
Flashing experiment at DLR M3.1

- Big challenges for the injection system concerning cryogenic environment :
  - cooling of the complete feed system including the injector with homogeneous temperature distribution
  - freezing air humidity → blocked injector or valves



- New cryogenic temperature adjustment and injection system (M3.3) was constructed

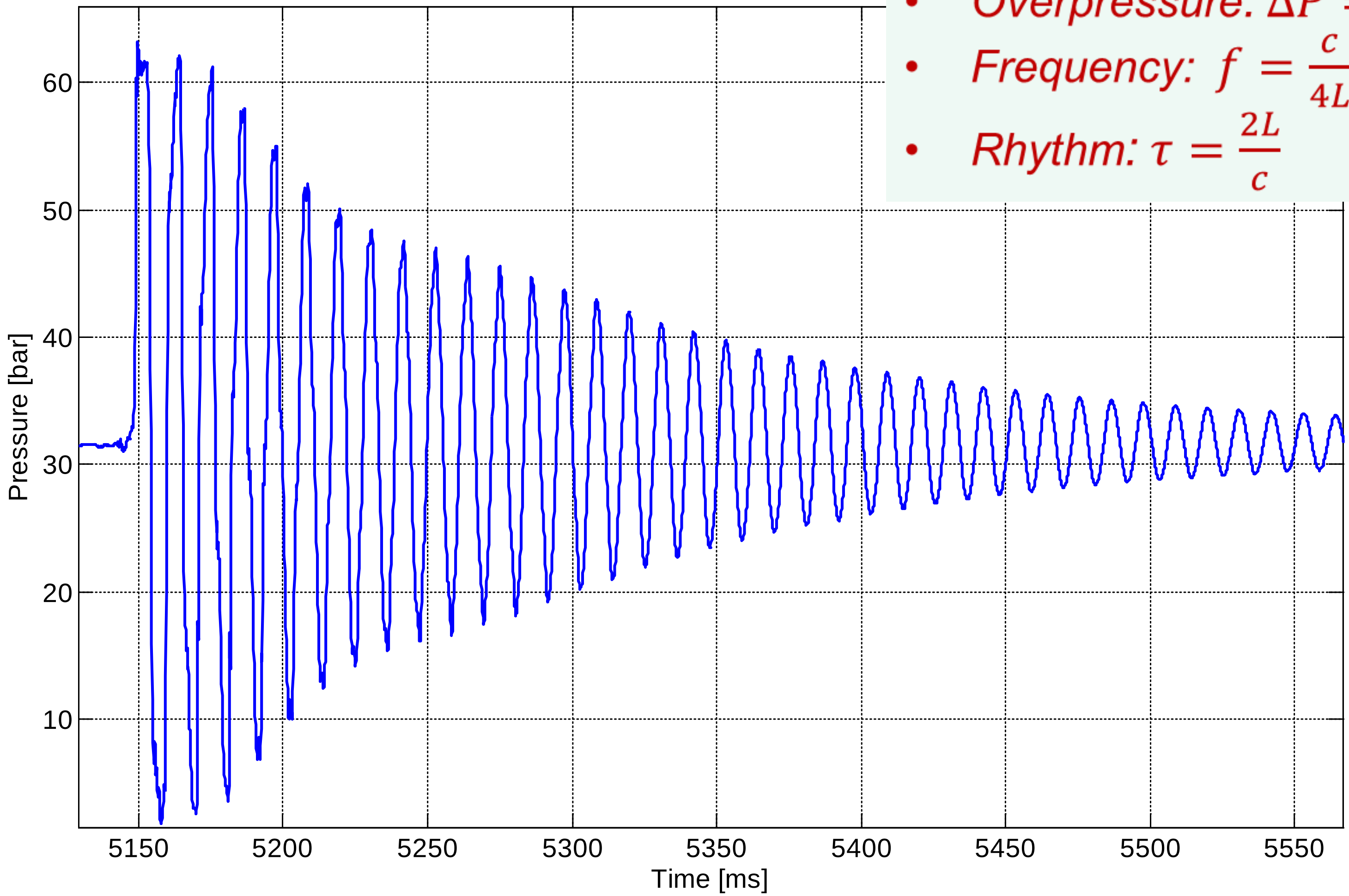
→ detailed investigation of LN2 & LOX flash boiling, see poster *Cryogenic Flash Boiling in Liquid Rocket Engines*



Flash boiling of LOX at M3.1
left: config. #1 ($L/D \approx 22$, $T_{inj} = 94\ K$) →heterog. nucleation
right: config. #2 ($L/D \approx 1$, $T_{inj} = 113\ K$) →homog. nucleation

Test Case:
Water Hammer with cavitation

Introduction: water hammer



- *Overpressure:* $\Delta P = \rho c \Delta V$
- *Frequency:* $f = \frac{c}{4L}$
- *Rhythm:* $\tau = \frac{2L}{c}$

Introduction: water hammer

In a LRE is of particular importance for LOx feedline (high density and speed of sound)

Cavitation => GOx : ignition hazard due to adiabatic compression

Physics can be very complex:

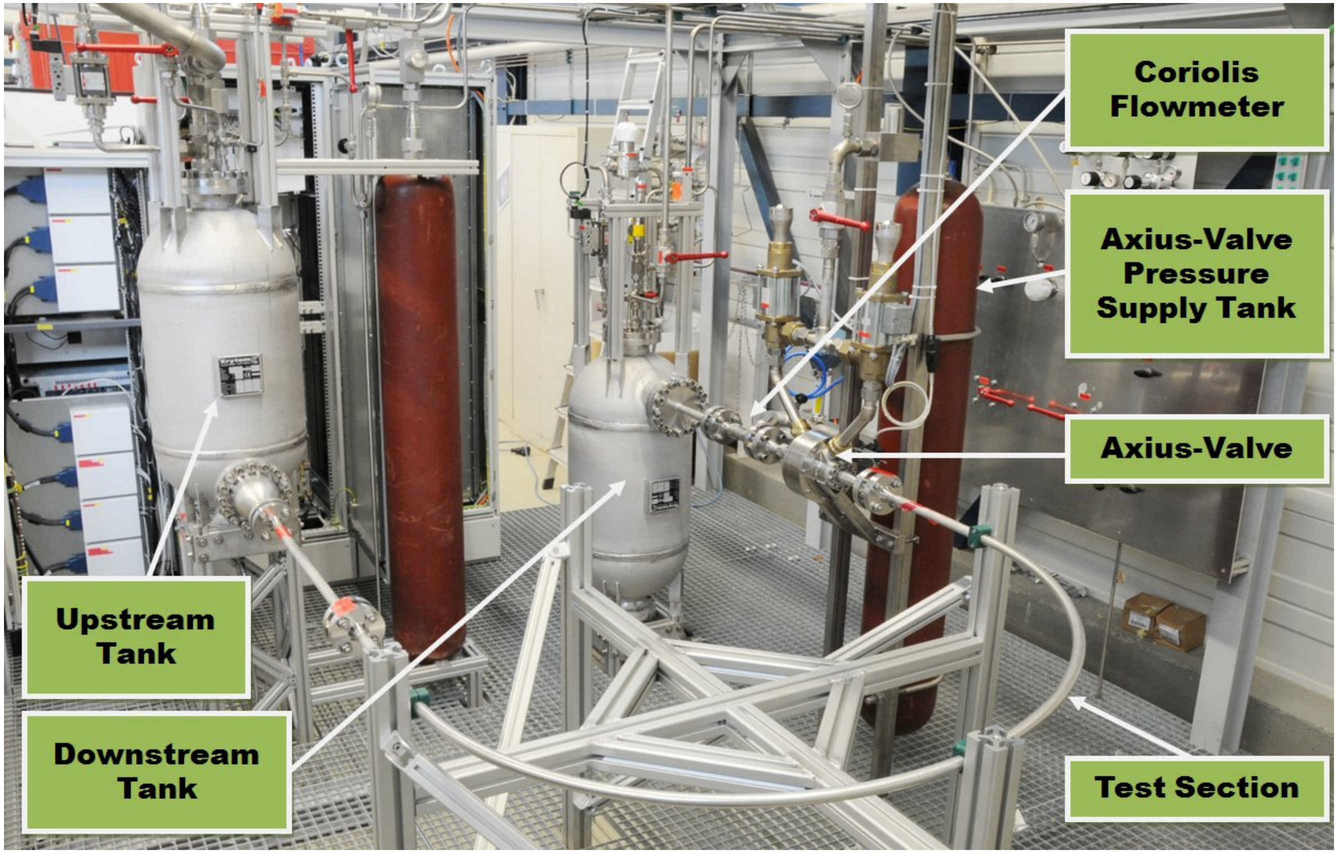
- Vaporous cavitation
- Gaseous cavitation (dissolved gas release)
- FSI

The flow not only two-phase but also *two-component*

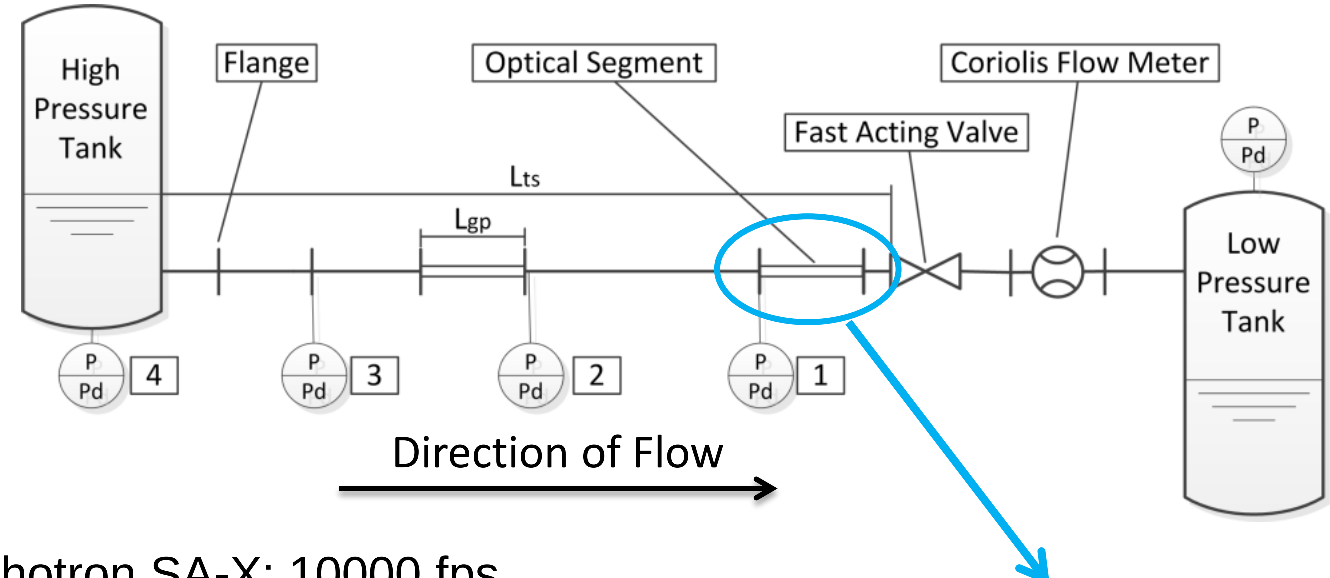
Test data needed for validation of the numerical tools.

Fluid Transient Test Facility: Water hammer

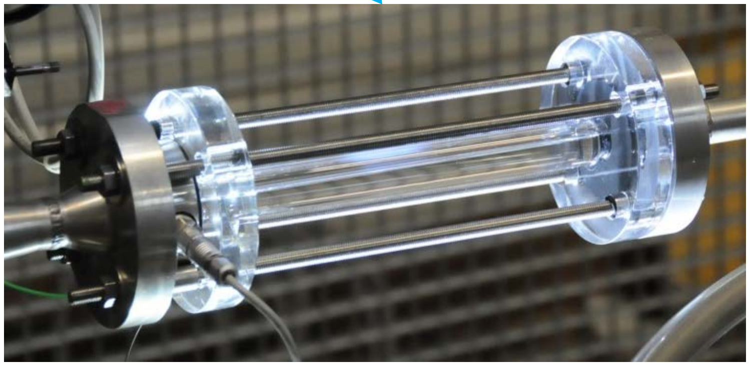
- Fluid: Water, Ethanol
- Tank pressure: 50bar
- Test section Pressure: 100bar
- Test section length, Valve to Tank: 7.34m
- Valve closure time: 11ms
- Pressurizing Gas: N2, He
- Static and dynamic pressure sensors
- Strain gages and accelerometers for FSI
- Possibility of quartz window for optical investigation (high speed camera up to 100 kfps)
- Modularity for geometry changes, different test-sections



Experimental set-up for flow visualisation



- Photron SA-X: 10000 fps
- Shutter: 1/18604s
- LED backlight
- Optical diffusor
- 710 x 115 pixels
- 0.28 mm/pixel



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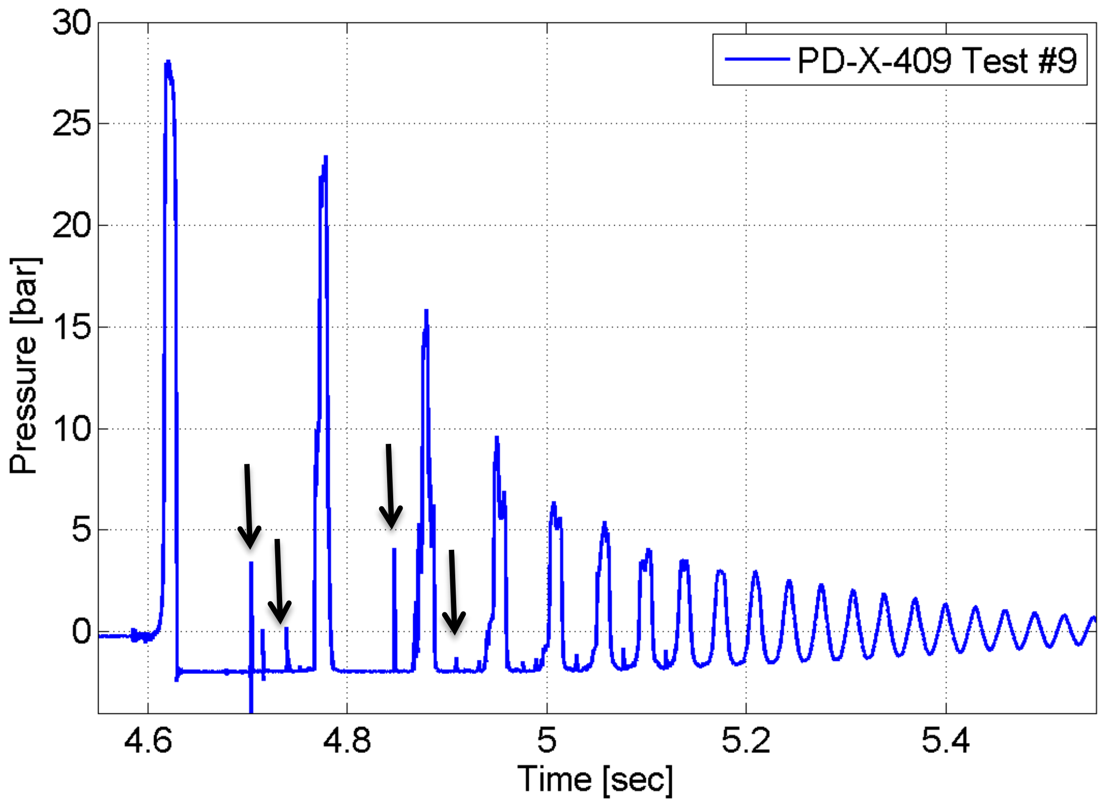
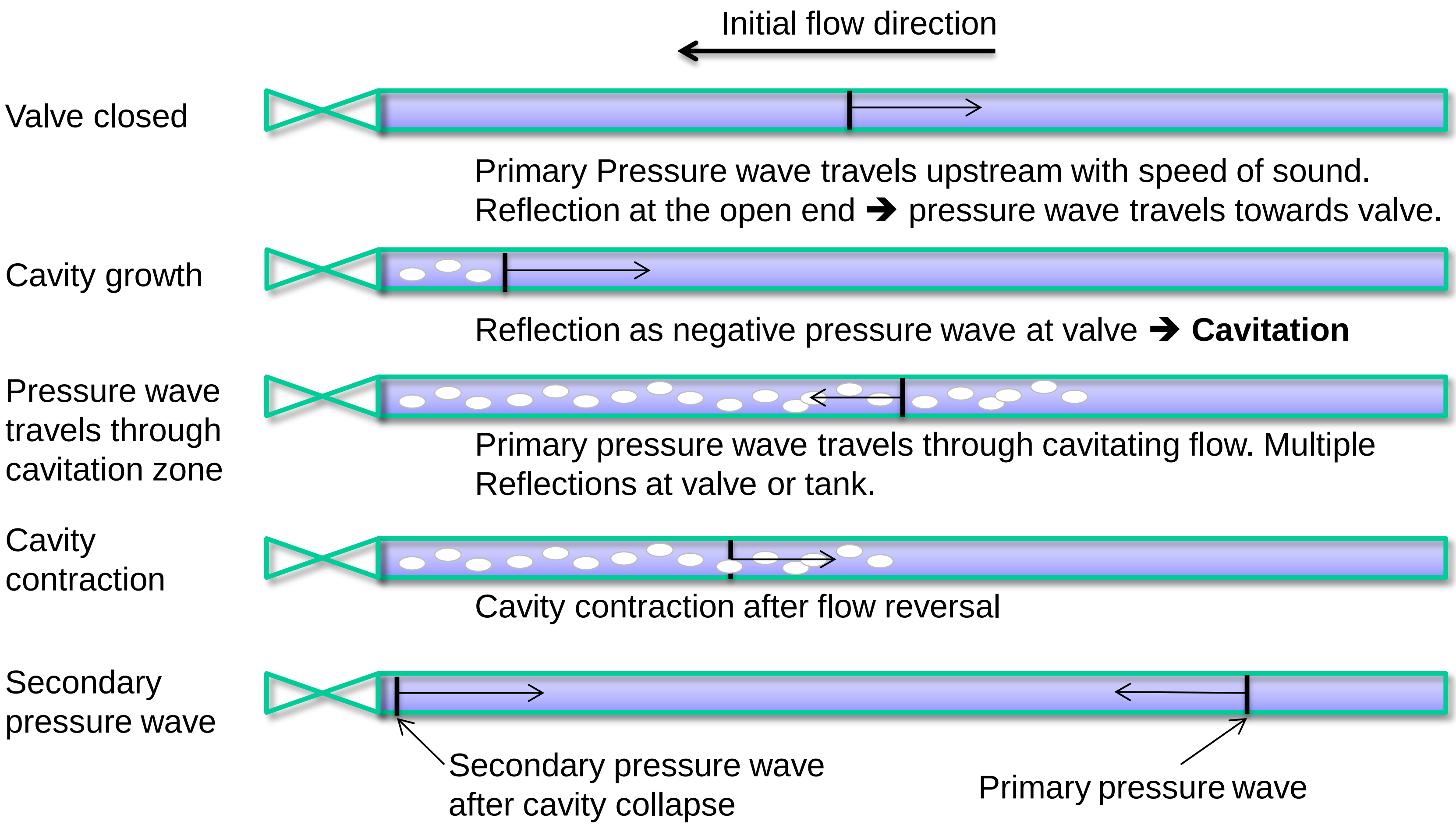
Water hammer with cavitation: pressure spikes

- Only in tests with cavitation
- Test #9:
  - Mean tank pressure: 2bar
  - Flow velocity prior to valve closing: 2.08m/s

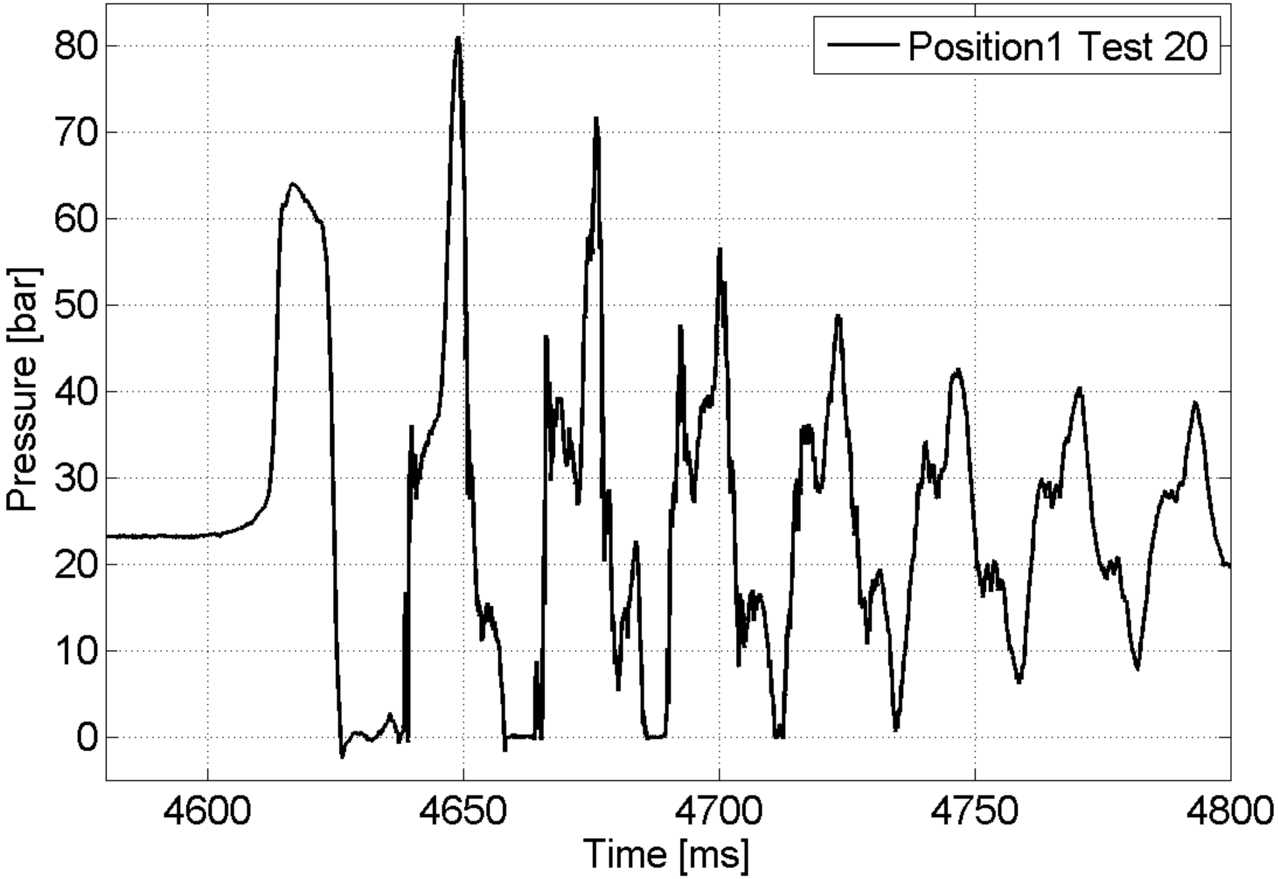


Water hammer with cavitation



Water hammer with cavitation: higher 2nd peak

- Only in tests with cavitation
- Test #20:
  - Mean tank pressure: 23.8bar
  - Flow velocity prior to valve closing: 3.14m/s



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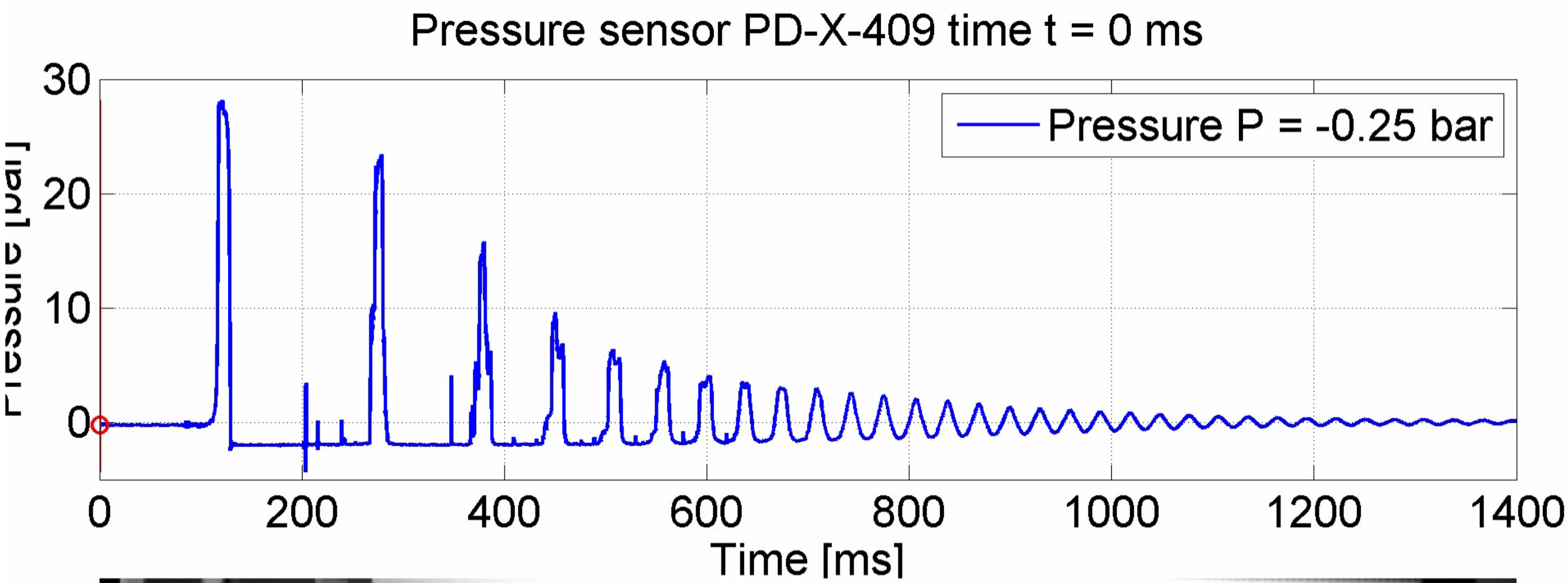
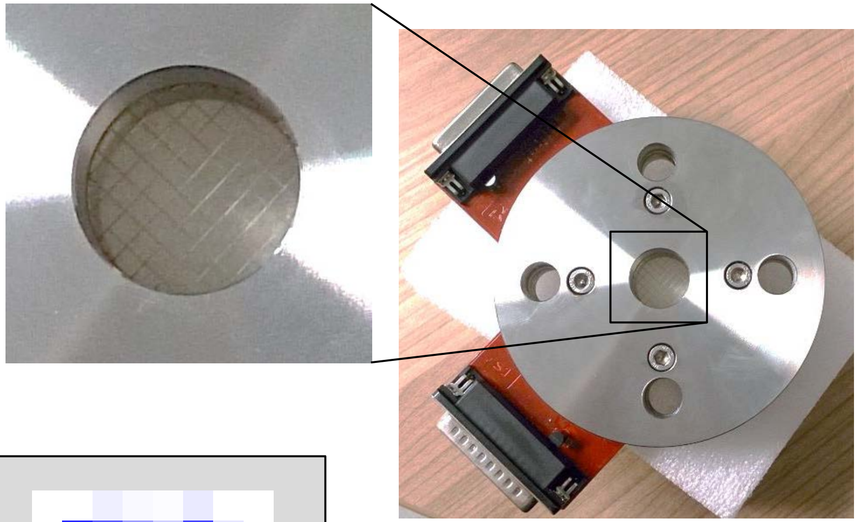
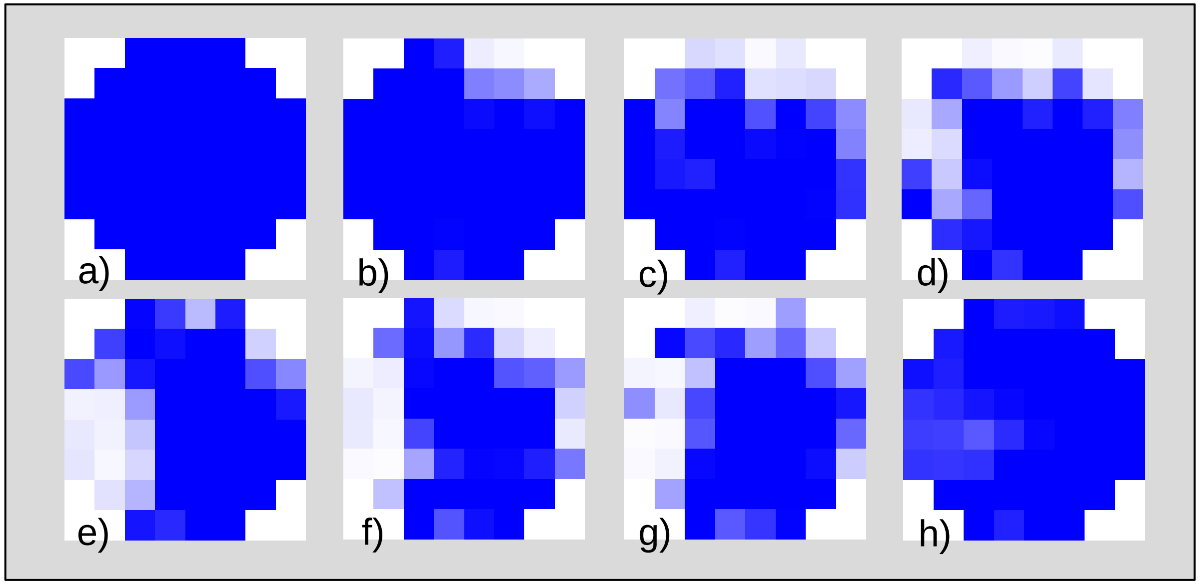
Water hammer with cavitation: flow visualisation



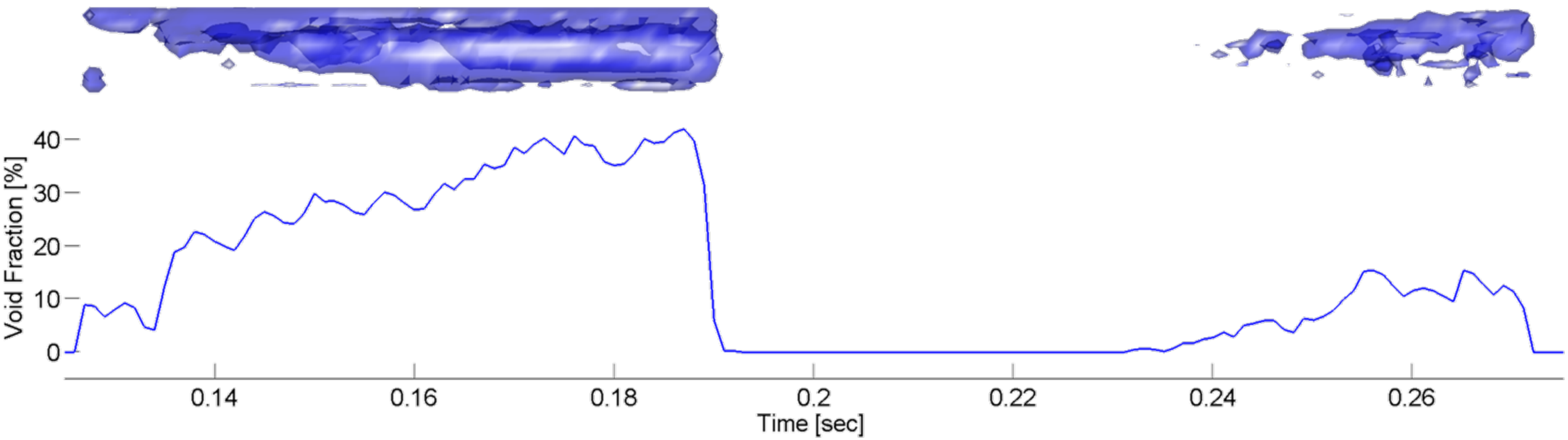
Water hammer visualisation technique: wire mesh sensor

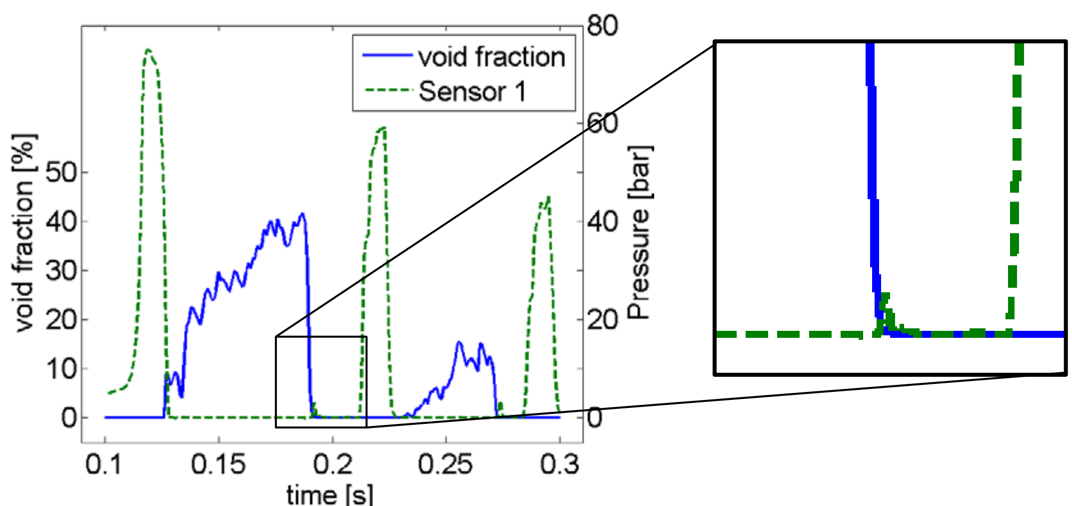
- Sensor from Helmholtz Zentrum Dresden Rosendorf (HZDR)
- Two-dimensional void fraction over the cross section with a frame rate of 10000 fps
- 8x8 grid: 64pixel





Water hammer: wire mesh sensor





Test #	9
Mean tank pressure (bar)	7
Initial flow velocity (m/s)	5.15

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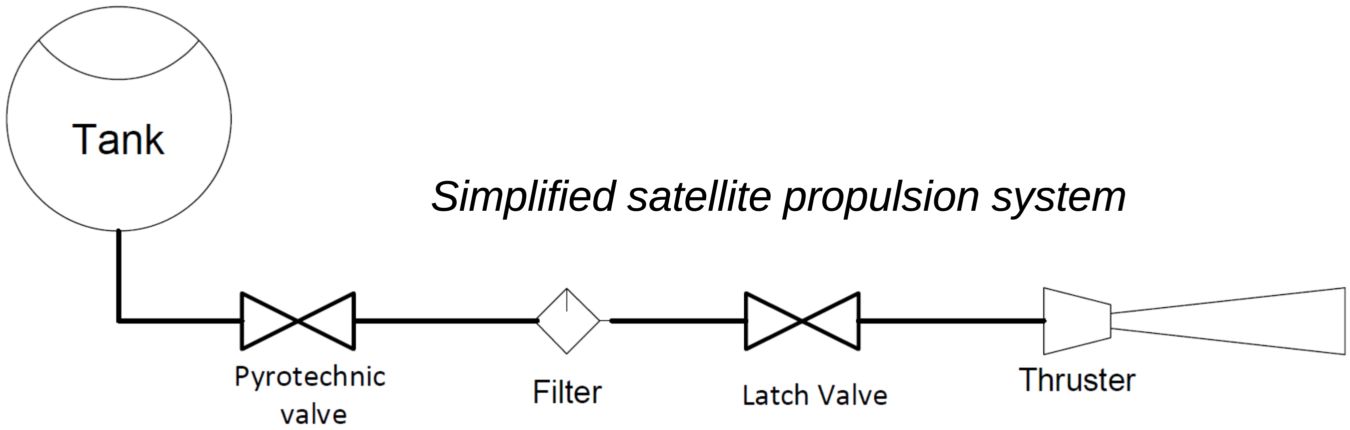
Test Case:
Priming

Introduction: what is priming ?

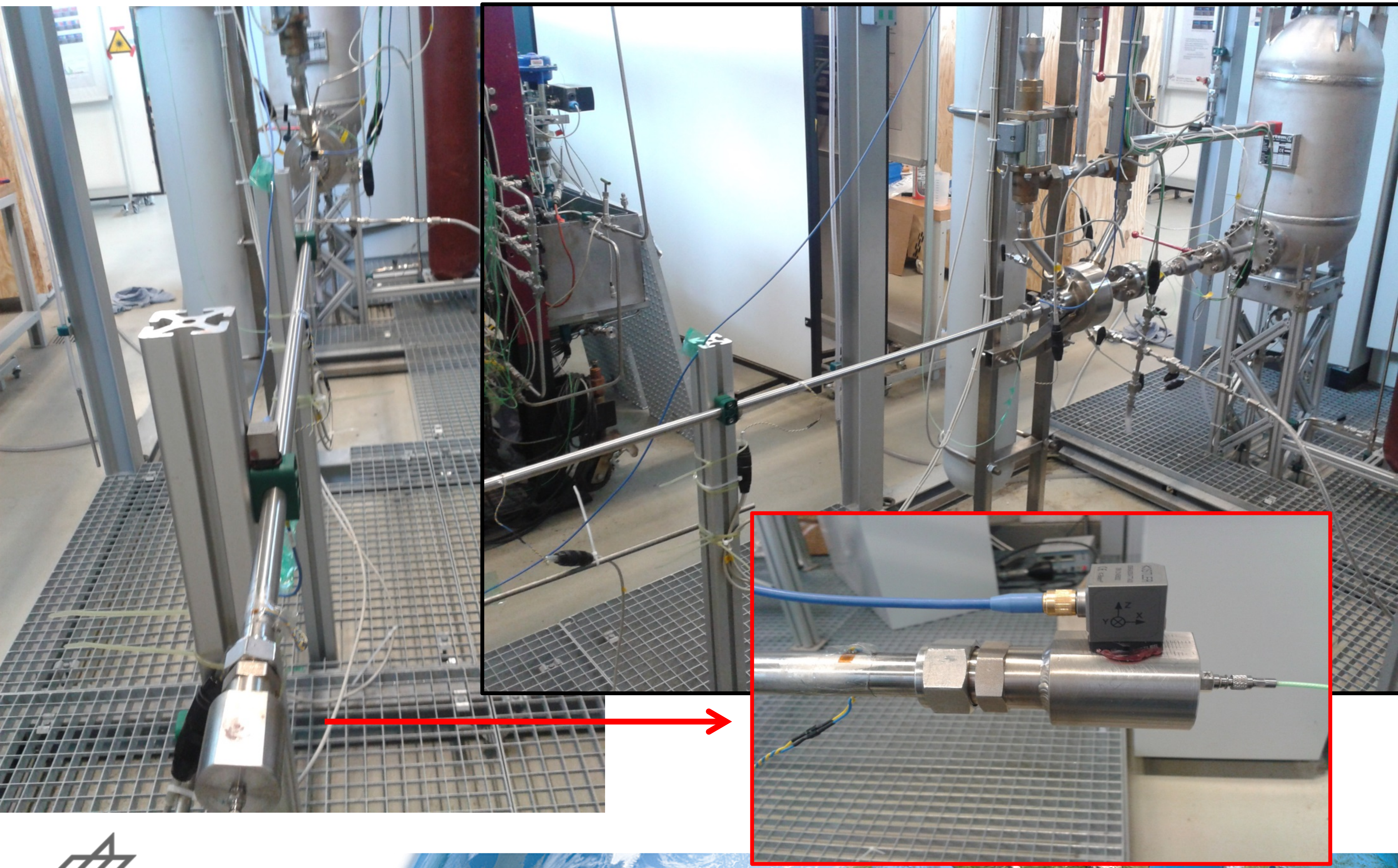
Priming: opening of the isolation valve causes the filling of the evacuated feedline => severe pressure peak



Pressure peak > 250 bar =>

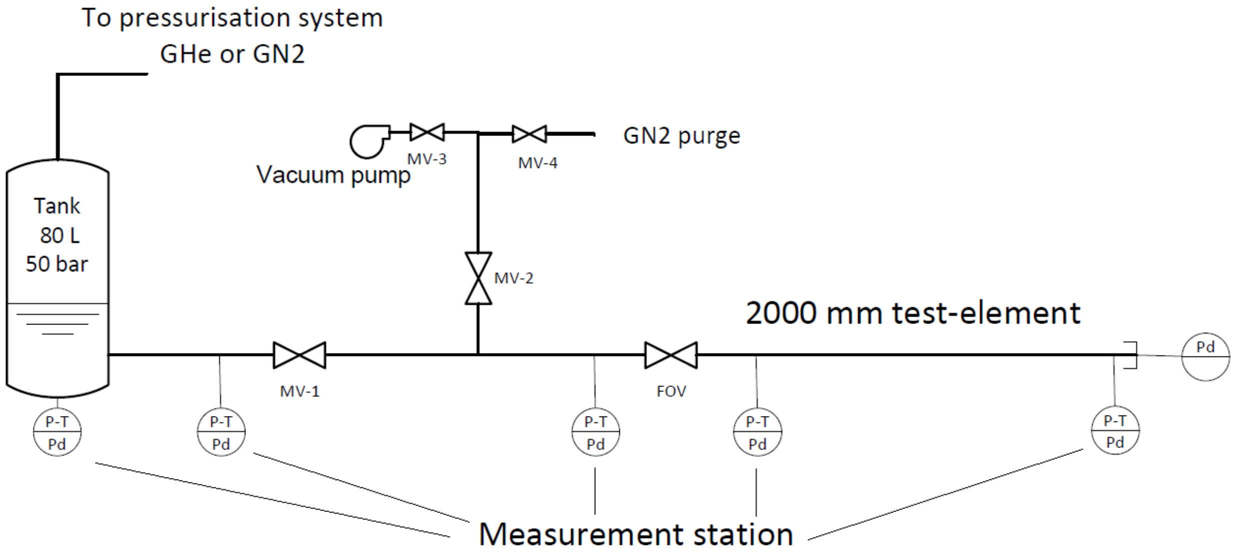
1. Structural failure
2. Adiabatic compression detonation (monopropellant)

M3.5 Fluid transient Test-bench : priming configuration



Test procedure

- Purging GN2 via MV-2
- Evacuate
- Close MV-2 and FOV
- MV-1 open, manual prime
- Test run



Test-element is a OD 2000mm long 19x1.44 mm pipe, stainless steel
High mass flow, e.g. ATV feedlines

For satellite usually 6.35 mm x 0.41 mm titanium alloy

Test-matrix: effect of dissolved gas (gaseous cavitation, *aka Coca-Cola effect*)

tank pressure: 20 bar

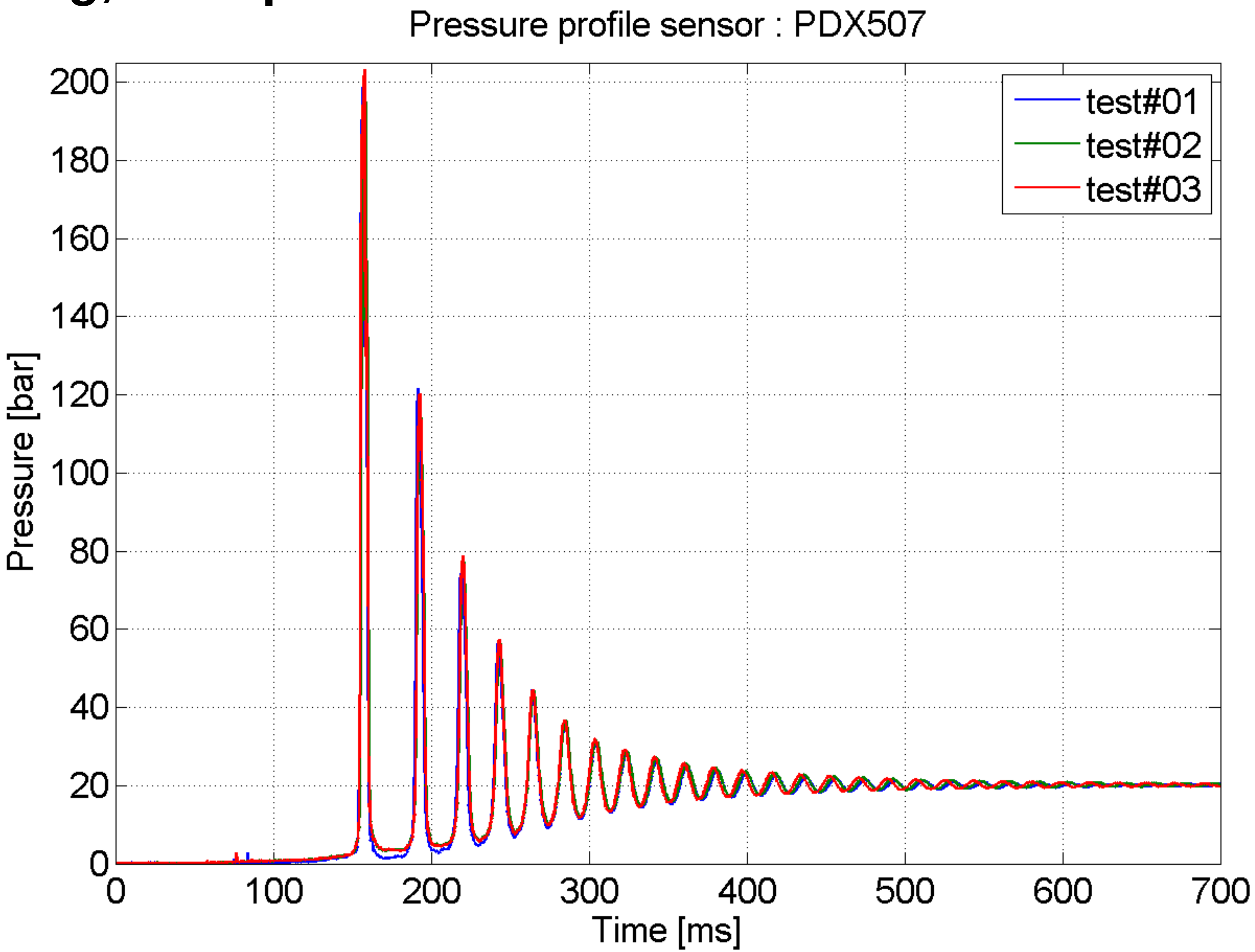
P line, water (Pvap = 20 mbar)	P line, ethanol (Pvap = 42 mbar)
Deareated	Deareated
1 bar GN2 saturated	1 bar GN2 saturated
10 bar GN2 saturated	-
20 bar GN2 saturated	20 bar GN2 saturated
20 bar GHe saturated	-

Dissolved gas content

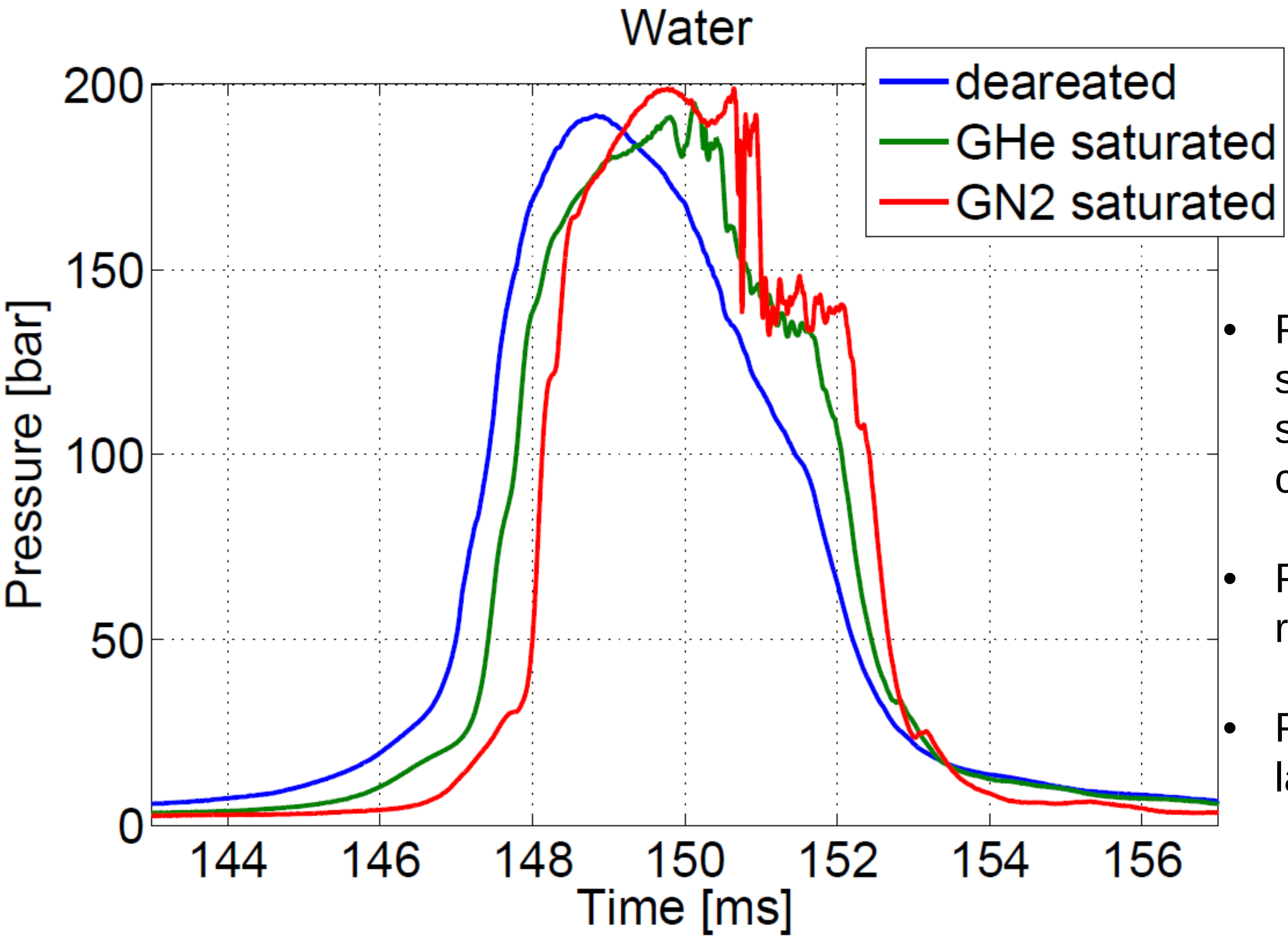
Gas saturation pressure	water	ethanol
1 bar	20.8 mg/kg	220 mg/kg
20 bar	380 mg/kg	4200 mg/kg

Tests are repeated 3 times to examine reproducibility

Priming, example

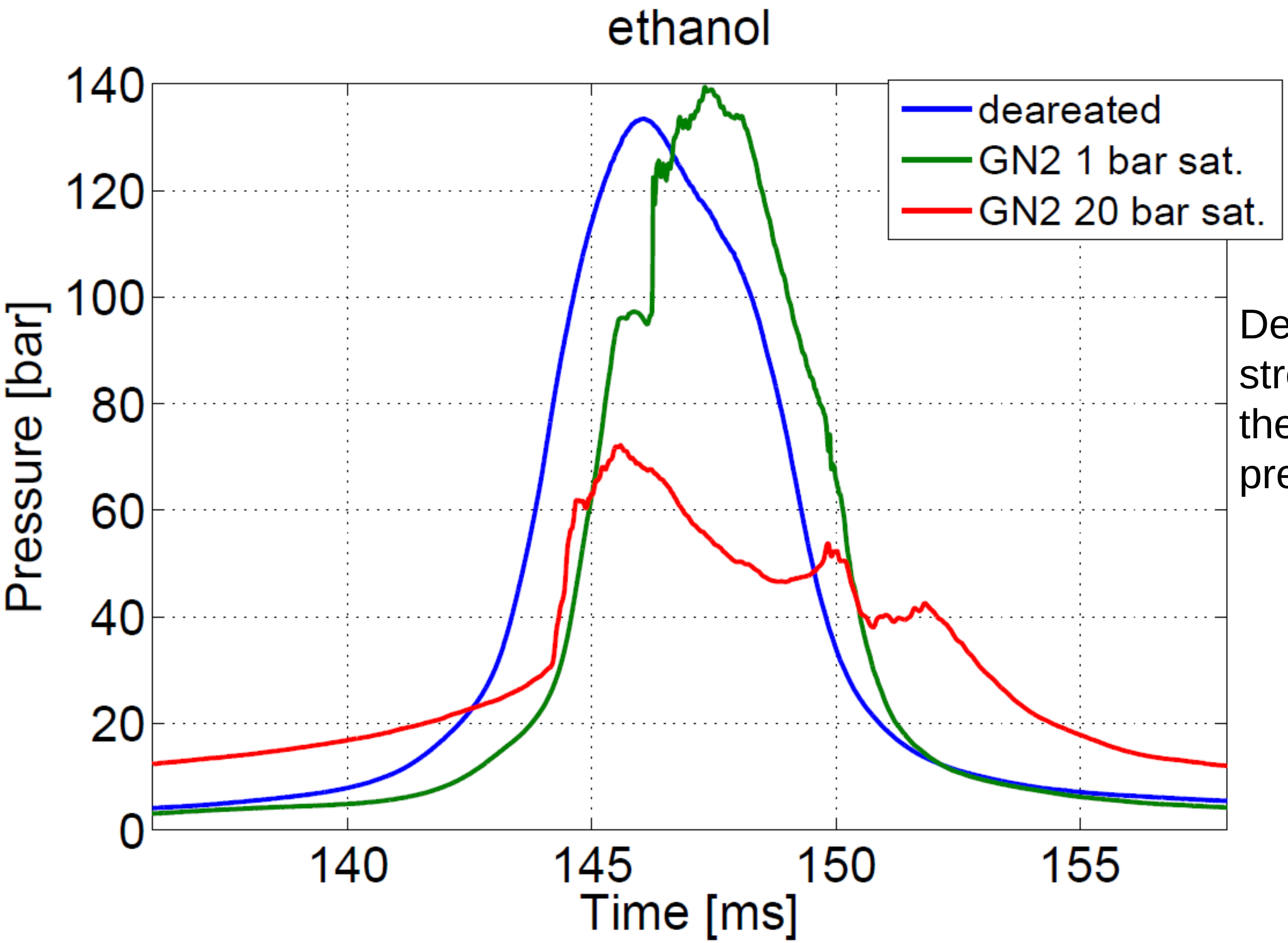


Results for water



- Pressure peak slightly higher at saturated condition
- Profile is more rough at saturated
- Peak time ~1 ms later at saturated

Results for ethanol



Desorbed gas strongly increases the damping of the pressure peak

Priming

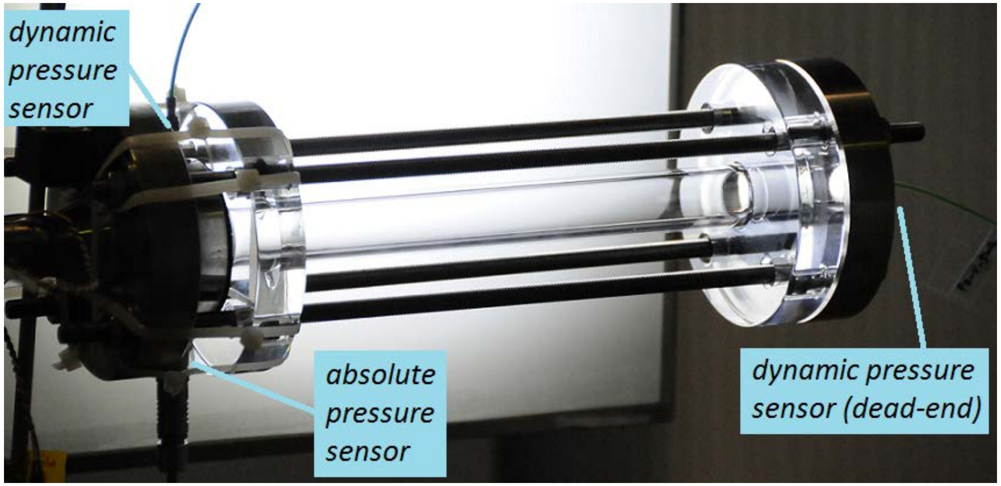
The effect of the dissolved gas is clear: but how does it act?

<u>Hypothesized mechanism:</u>

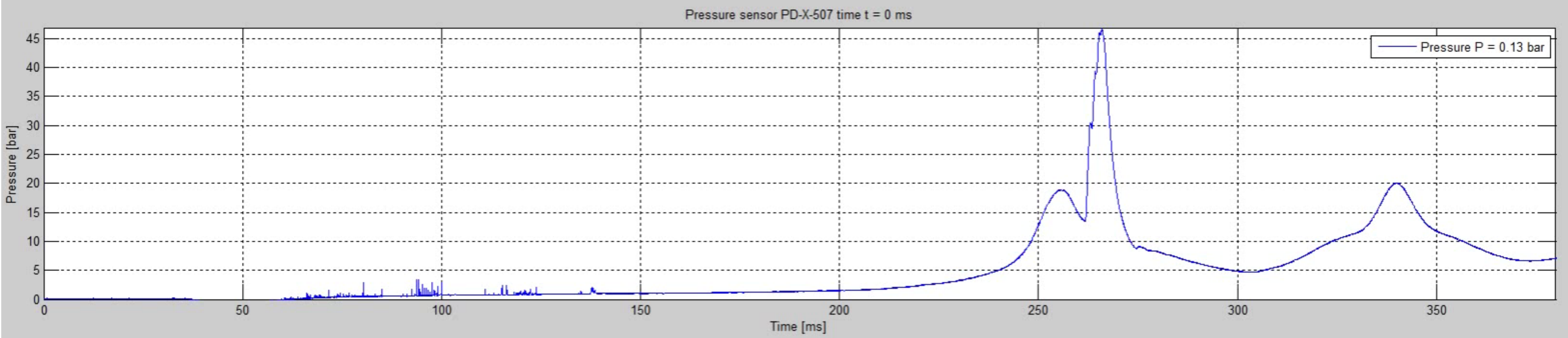
the desorption of the dissolved gas will create gas pocket inside the liquid, and the later could be modelled as multiple slugs that impinge one on the others resulting in the step-plateau profile

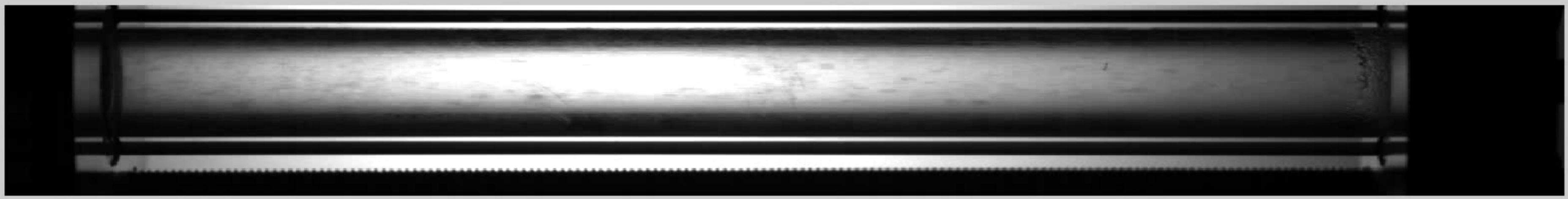
We need to see inside!

quartz pipe at the dead-end + high speed camera



Priming





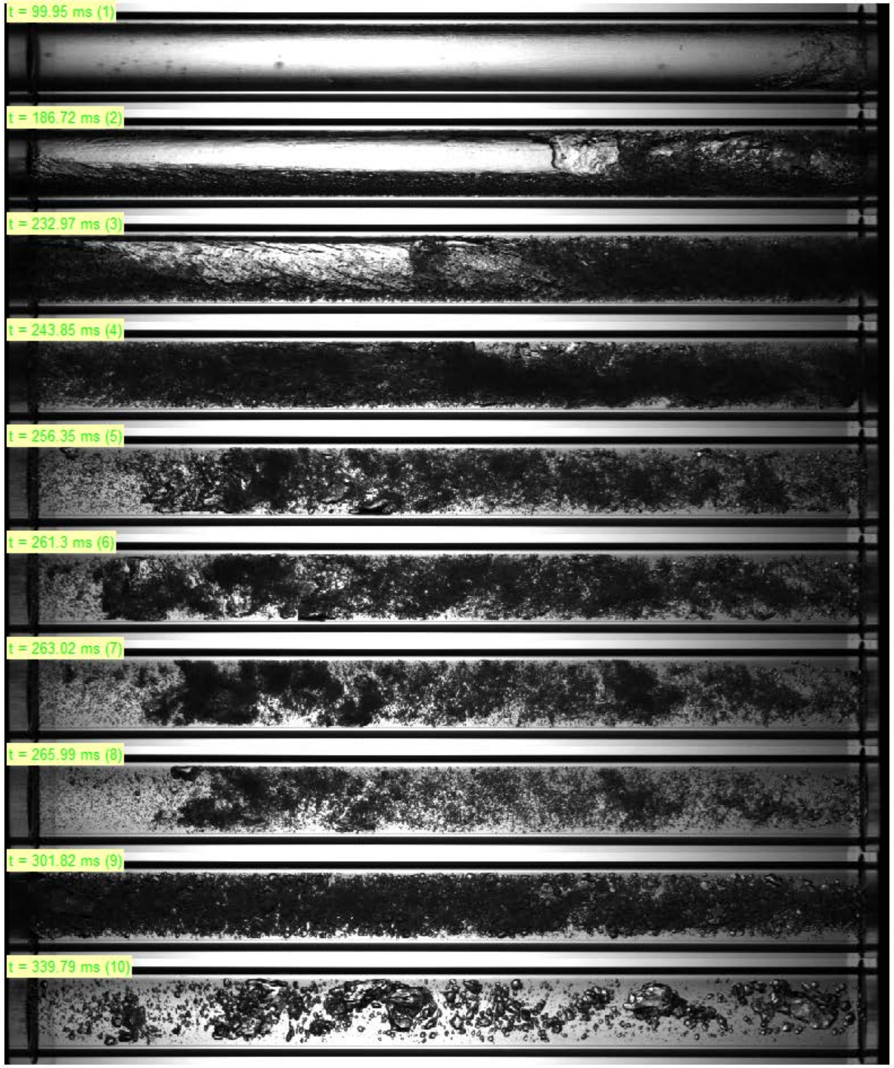
Test conditions:

- Tank pressure : 9 bar
- saturated water
- Line pressure: 12 mbar

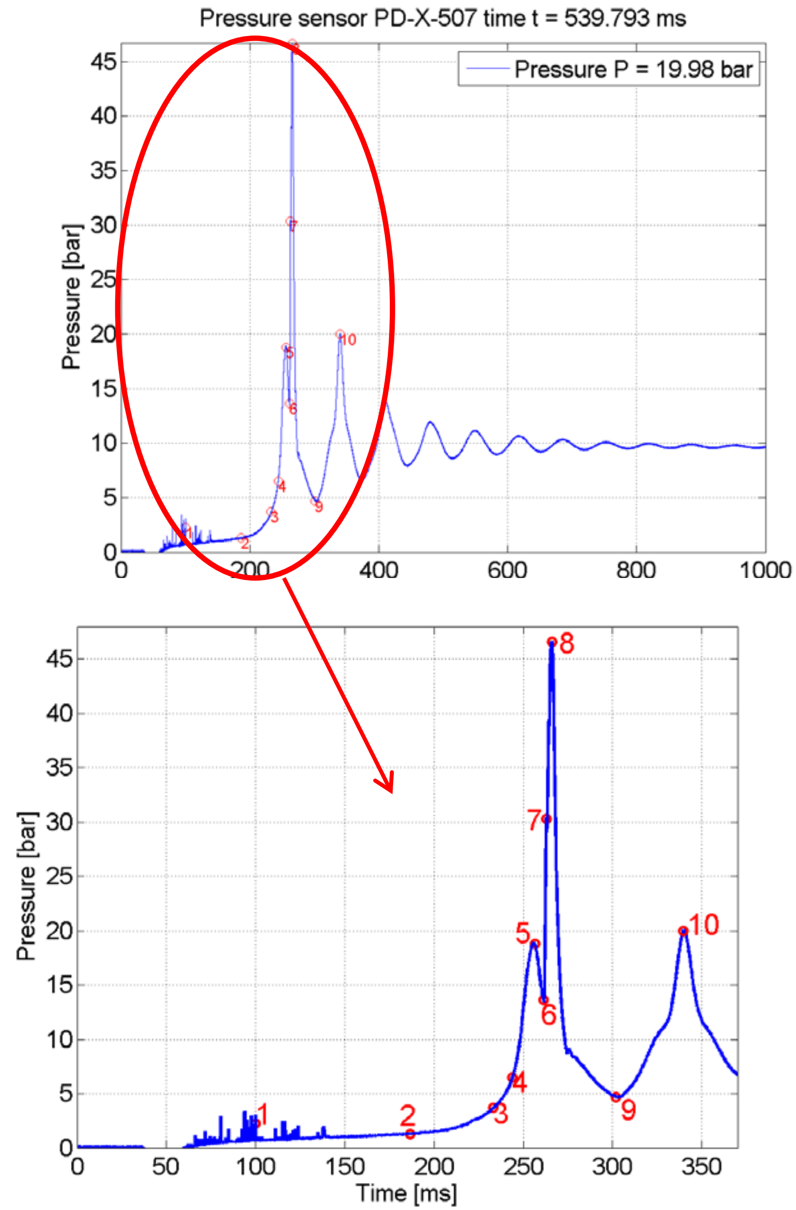
Camera setting:

- Frame rate: 19200 fps
- Resolution: 1024x84
- 250 ms at 120 fps (x160)

Priming



t = 99.95 ms (1)
t = 186.72 ms (2)
t = 232.97 ms (3)
t = 243.85 ms (4)
t = 256.35 ms (5)
t = 261.3 ms (6)
t = 263.02 ms (7)
t = 265.99 ms (8)
t = 301.82 ms (9)
t = 339.79 ms (10)



Pressure sensor PD-X-507 time t = 539.793 ms
Pressure P = 19.98 bar
Pressure [bar]
0
5
10
15
20
25
30
35
40
45
0
200
400
600
800
1000
1
2
3
4
5
6
7
8
9
10
Pressure [bar]
Time [ms]
0
50
100
150
200
250
300
350

Priming/conclusions

Decreasing the line pressure causes *higher pressure peak, higher wave frequency, less wave attenuation* (as expected) but only down to Psat:

- when the $P_{line} < P_{sat}$ no remarkable differences any more

The effect of the dissolved gas is not negligible:

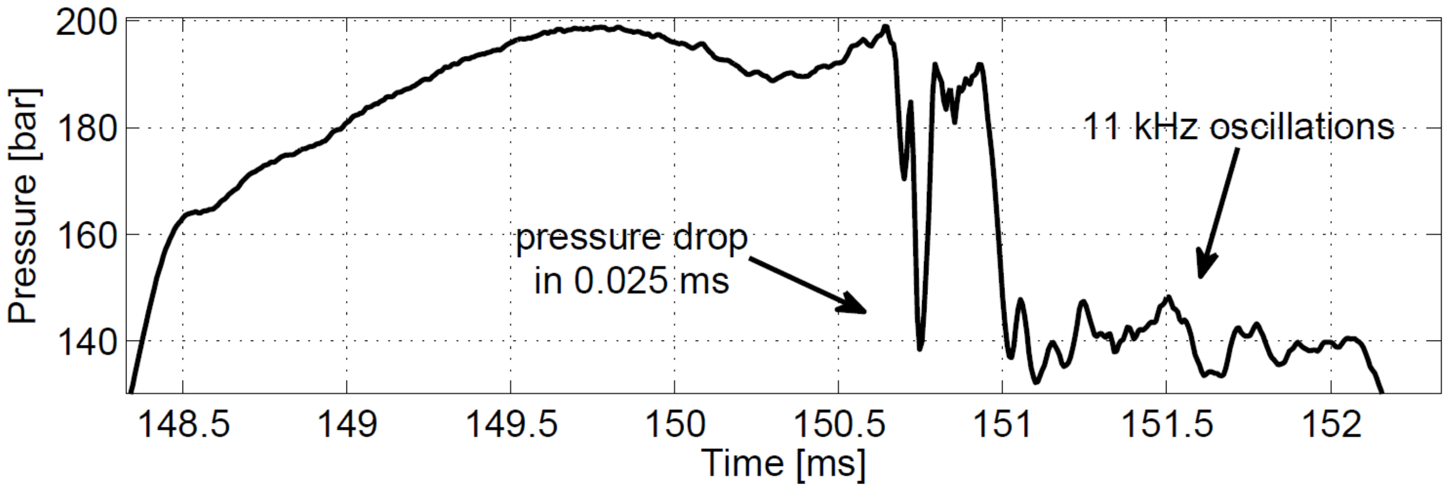
the desorption of the dissolved pressurizing gas affects the profile of the pressure peak :

- rougher shape with a multiple step-plateau profile
- pressure peak is ~ 1 ms delayed
- pressure peak can be slighlty higher!

Hypothesized mechanism : desorption of gas will create gas pocket forming multiple liquid slugs

Cavitation and bubble collapse

A strong pressure spike appears during the evolution of the first peak => cavitation



Cavitation occurred only with dissolved gas in liquid:

- 1 bar GN2 sat. : P_{tank} ≥ 20 bar
- 20 bar GN2 sat. : P_{tank} ≥ 16 bar
- 20 bar GHe sat. : P_{tank} ≥ 26 bar

→ Clear effect of pressurizing conditions on the onset of cavitation

in fact: nucleation rate increases;
surface tension decreases…

adiabatic detonation

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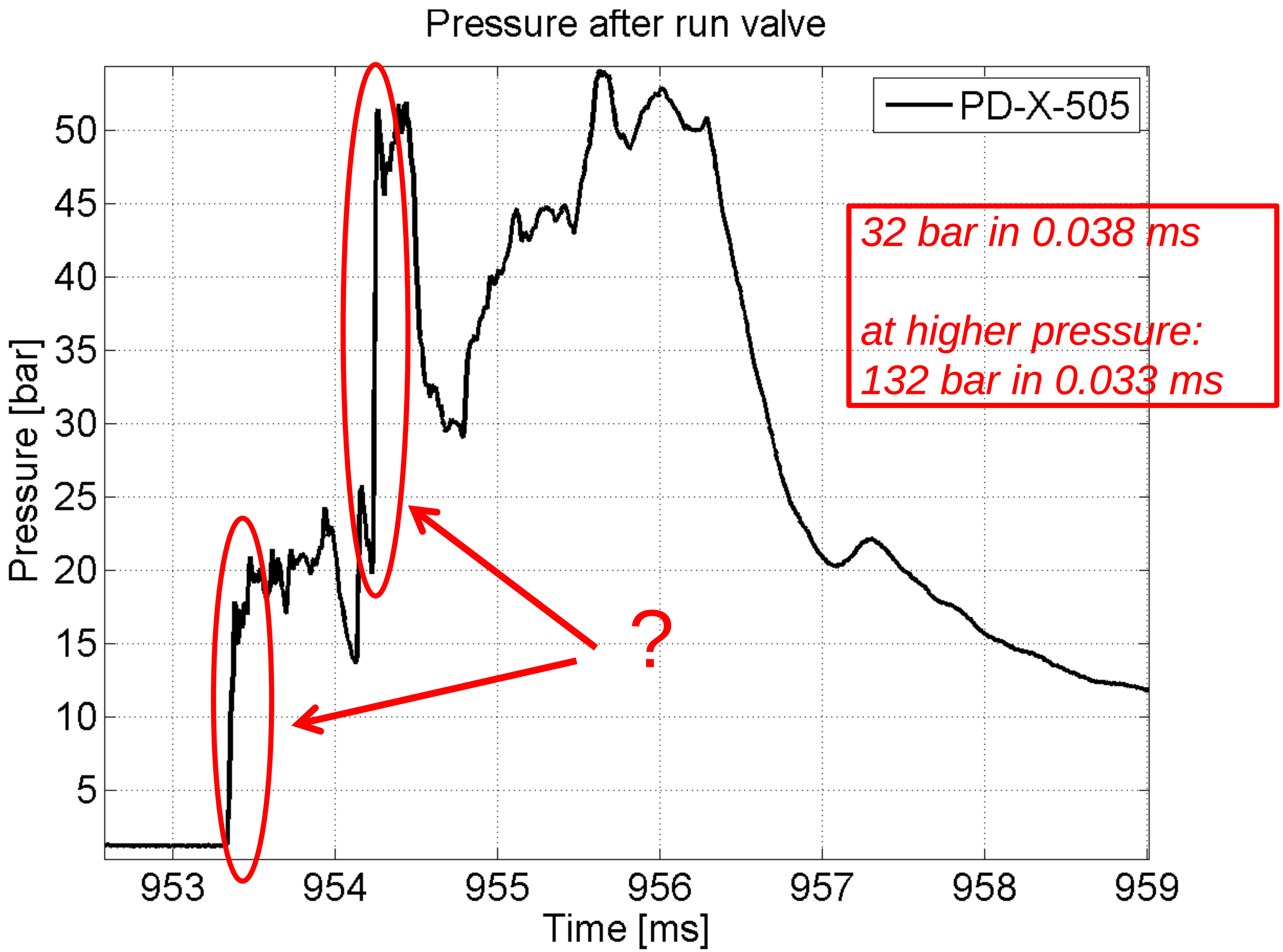
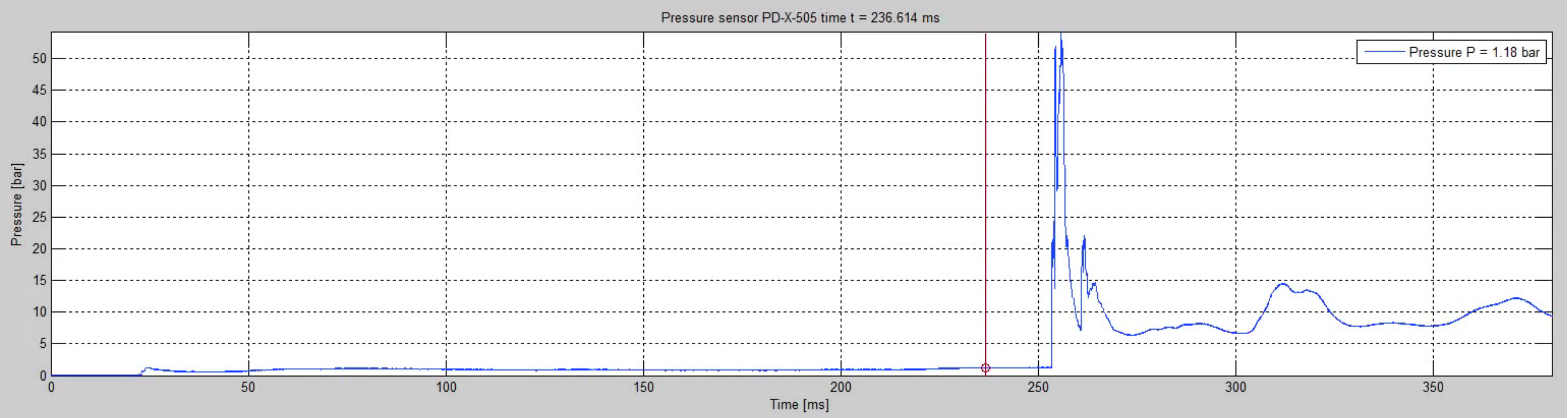
Priming: steep pressure gradient



Priming: HSI



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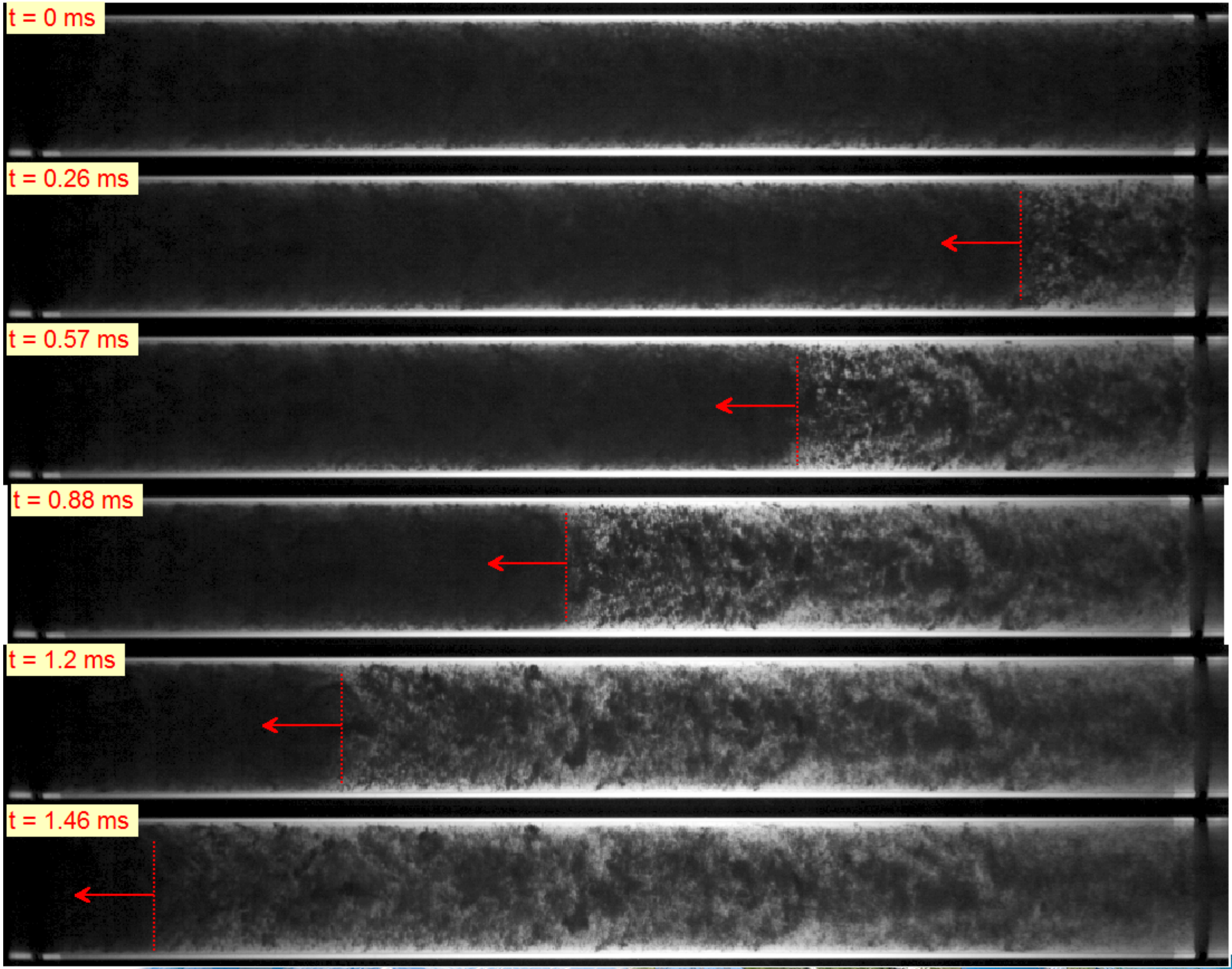
Cavitation-induced shock wave

Wave speed:
150 m/s

Mach 4 !

C. E. Brennen, *Cavitation and bubble dynamics*. Oxford University Press, 1995



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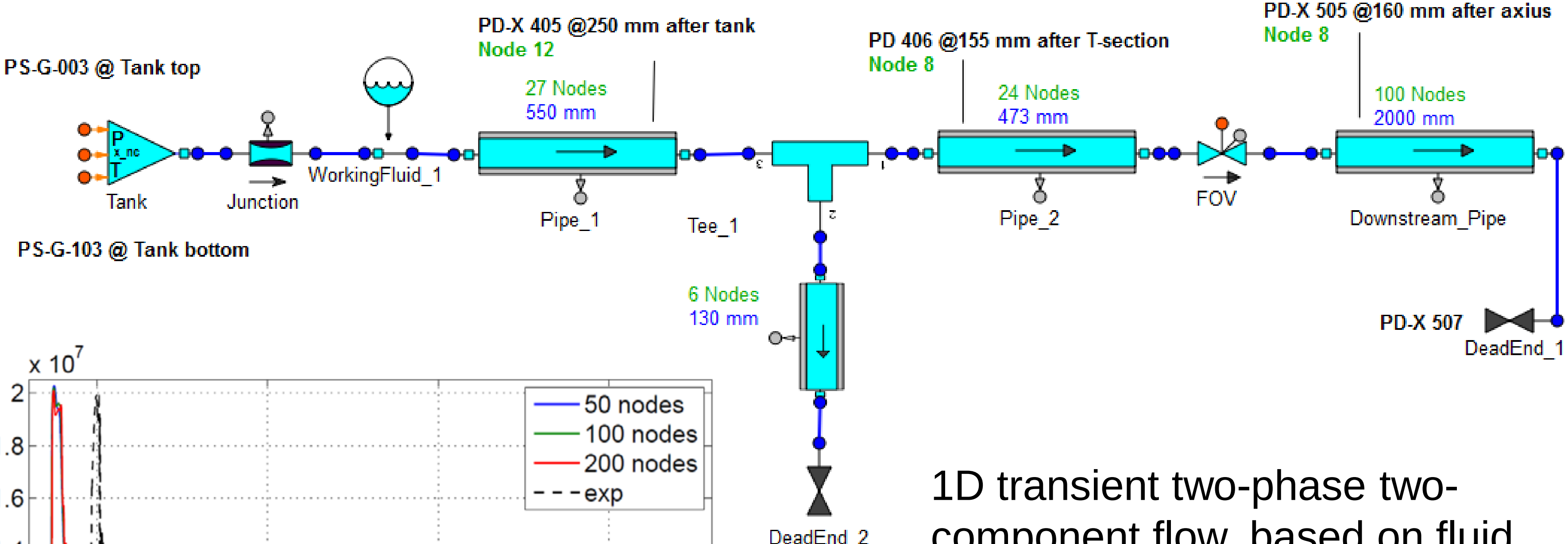
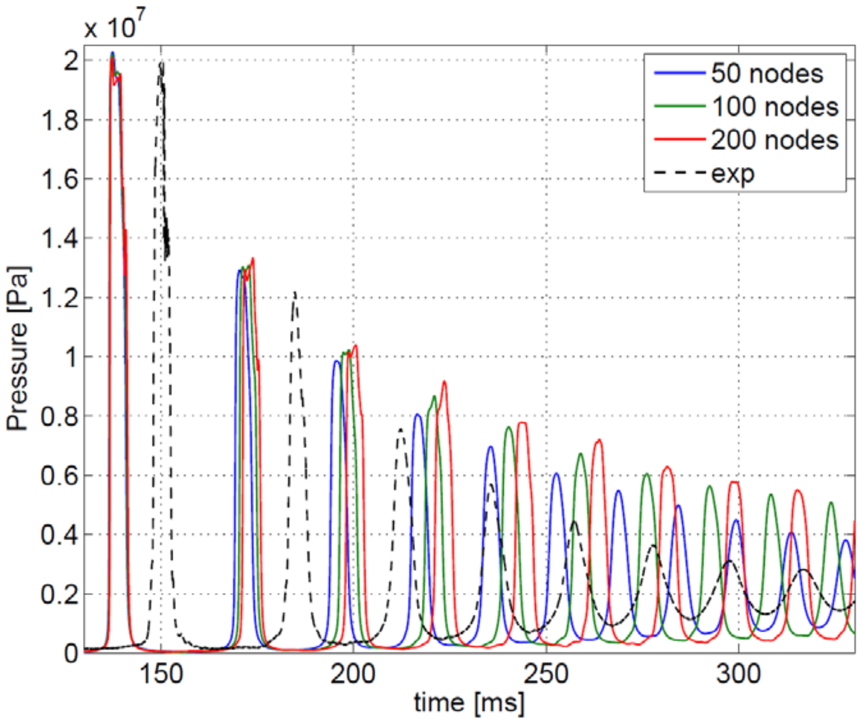
Numerical Modelling

Numerical modeling with EcosimPro/ESPSS



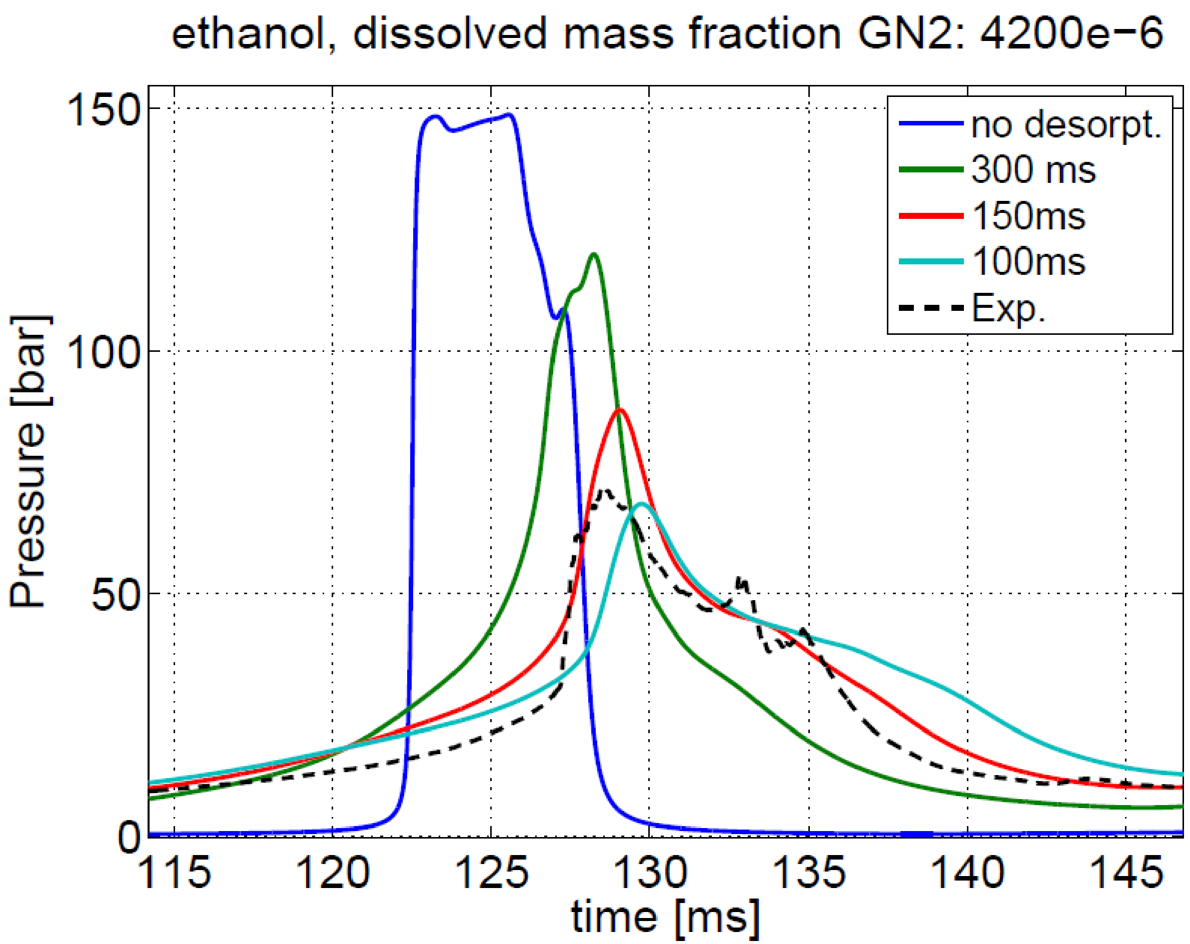


1D transient two-phase two-component flow, based on fluid conservation equations

Used in the design of propulsion systems, in particular for the pressurizing subsystem and feedline subsystem

Modeling of gas desorption

$$\dot{m}_{des} = C(P_{gas,sat} - P)$$



A simple gas release model can be included: it needs some empirical parameters, e.g. the desorption time constant

It definitely improves the simulation in terms of pressure peak

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Numerical Simulation of two-phase flow

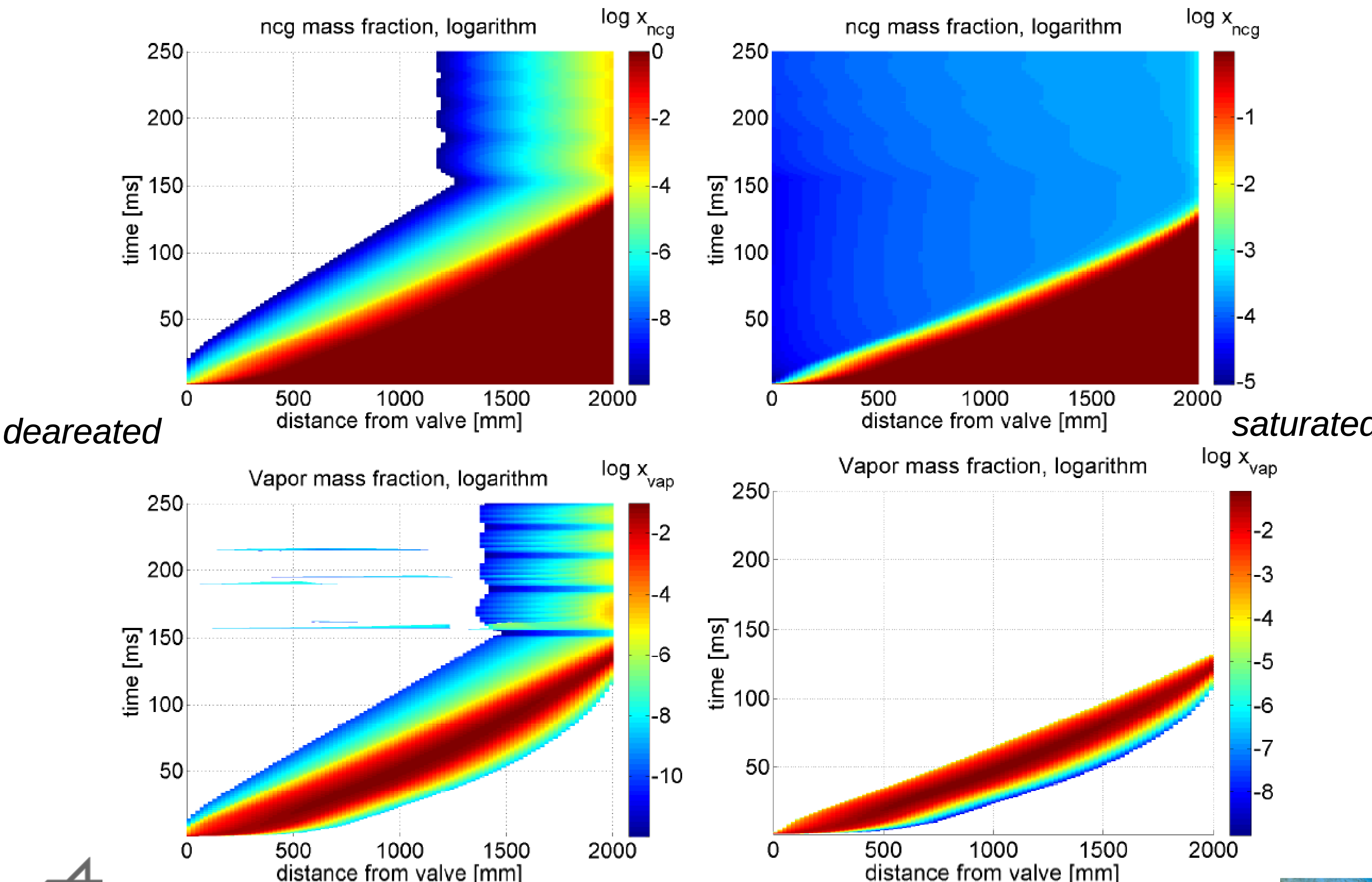
Numerical analysis allows to investigate phyisical quantities which are difficult or impossible to measure, e.g. :

- Void fraction, *α*
- Non-condensable gas mass fraction, NCG
- Vapor mass fraction, *x*
- Speed of sound, c

Based on the values of *α, NCG, x,* different flow regions can be defined:

region	α	x_{ncg}	x_{vap}
gas	1	1	0
gas-vapor	1	>0	>0
vapor	1	0	1
liquid-vapor	<1	0	>0
liquid-gas	<1	>0	0
liquid-gas-vapor	<1	>0	>0
liquid	0	0	0

Numerical Simulation of two-phase flow



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Priming/Conclusions

Propellant pressurizing conditions in tank play a not-negligible role:

- Pressure peak is affected by the gas saturation pressure
- Cavitation is intimately connected
- Formation of shock wave possible (detonation hazard)

Future work

- Further validation of the gas desorption model
- Inclusion of bubble dynamics

Thanks for your attention

Questions ?

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