Cryogenic Flash Boiling of Liquid Nitrogen Sprays

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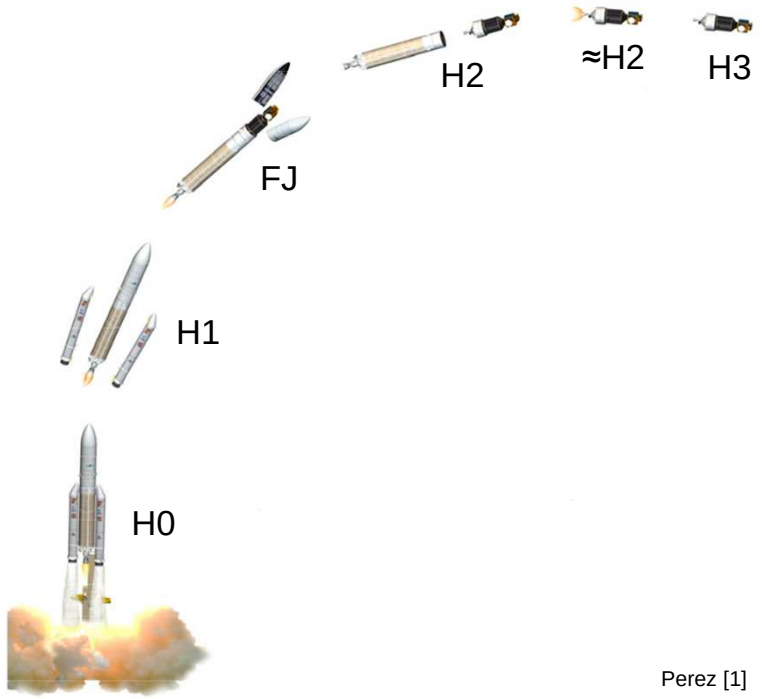
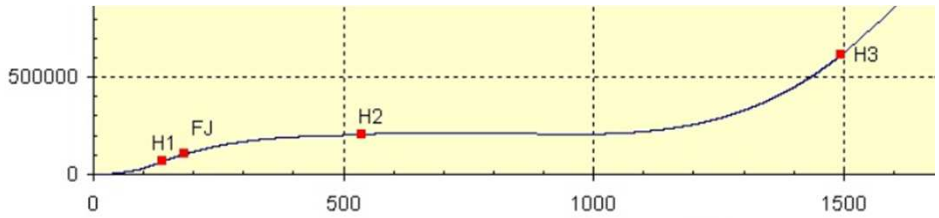
Motivation

- Re-ignitable upper stage engines
- New engine & propellant systems for RCS engines
  - → cryogenic oxygen (LOX), other green propellants
- LOX injection into vacuum (superheated condition)
  - → Flash boiling
- Characteristics of spray important for ignition process
  - → ignition?
  - → combustion stability?

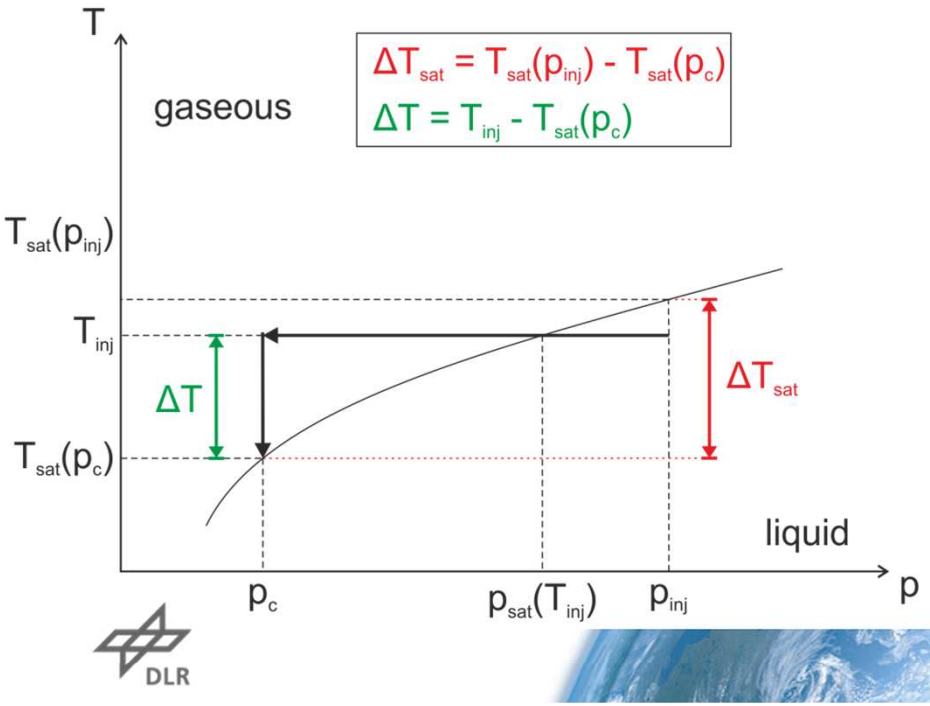


Perez [1]

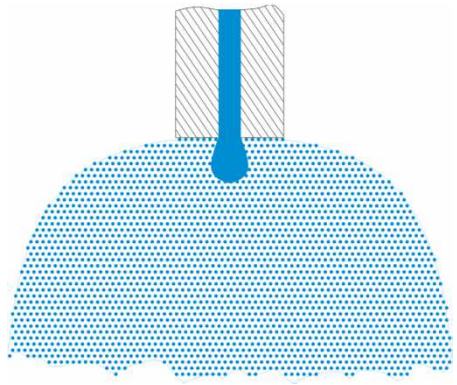


Superheat & Flash boiling

- Degree of superheat: $\Delta T^{*} = \frac{\Delta T}{\Delta T_{sat}} = \frac{T_{\mathrm{inj}} - T_{\mathrm{sat}}(p_{\mathrm{c}})}{T_{\mathrm{sat}}(p_{\mathrm{inj}}) - T_{\mathrm{sat}}(p_{\mathrm{c}})}$ or $R_{\mathrm{p}} = \frac{p_{\mathrm{sat}}(T_{\mathrm{inj}})}{p_{\mathrm{c}}}$



Aerodynamical break-up



Flash boiling

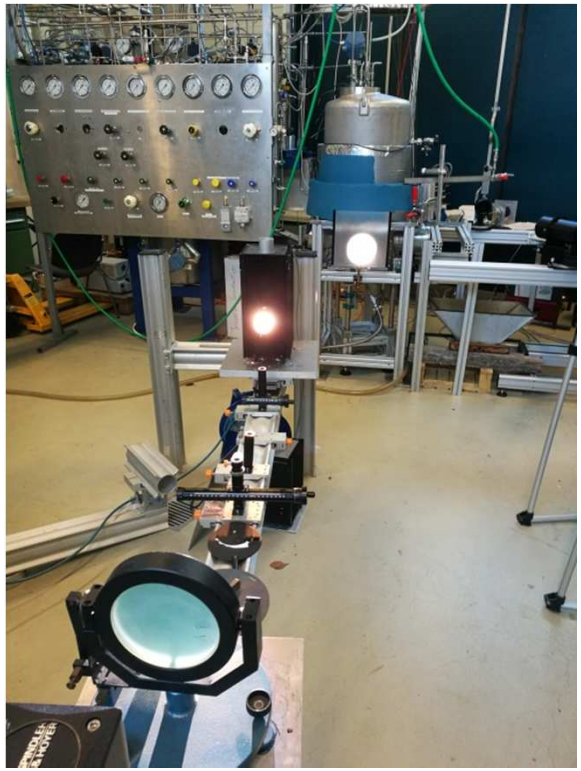
DLR

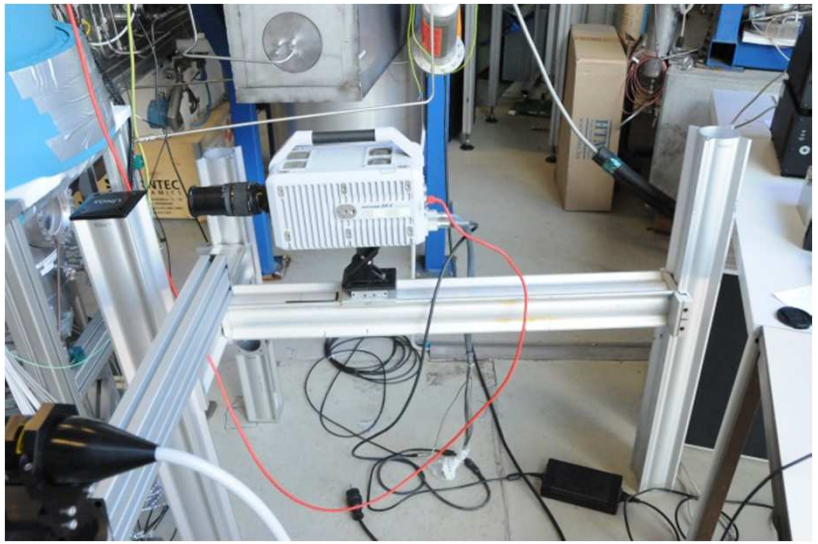
Test bench M3.3

- Cryogenic temperature adjustment and injection system: LN2 pressure tank, LOX run tank and injector unit
- Vacuum system
- Chill-down of the test bench

Highspeed Shadowgraphy Setup

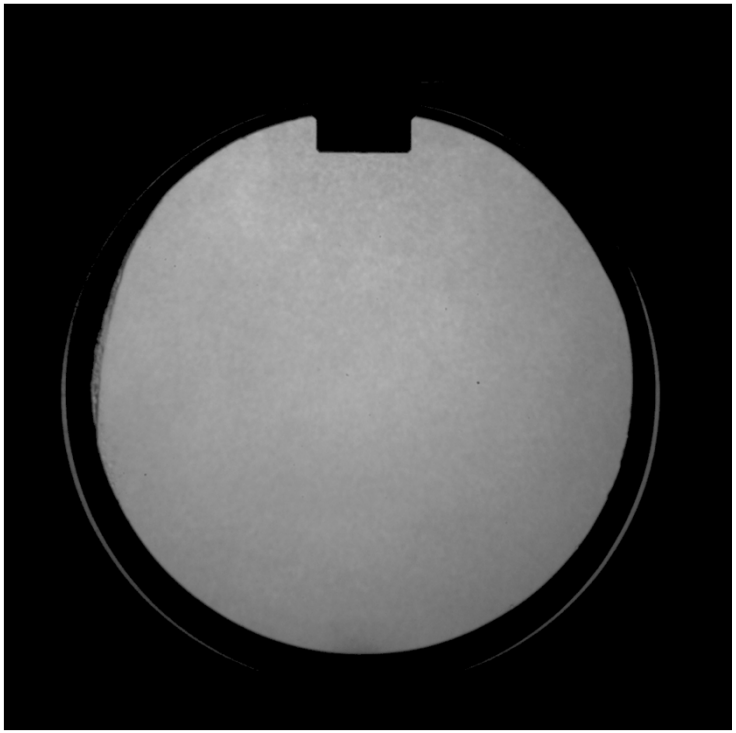
- Backlight Shadowgraphy
- Fastcam SA-X (Lense: Tamron AF 28-300mm F/3.5-6.3 Aspherical XR)
- Xe light source
- Translucent milk glass screen
- 10.000 fps
- 1024x1024

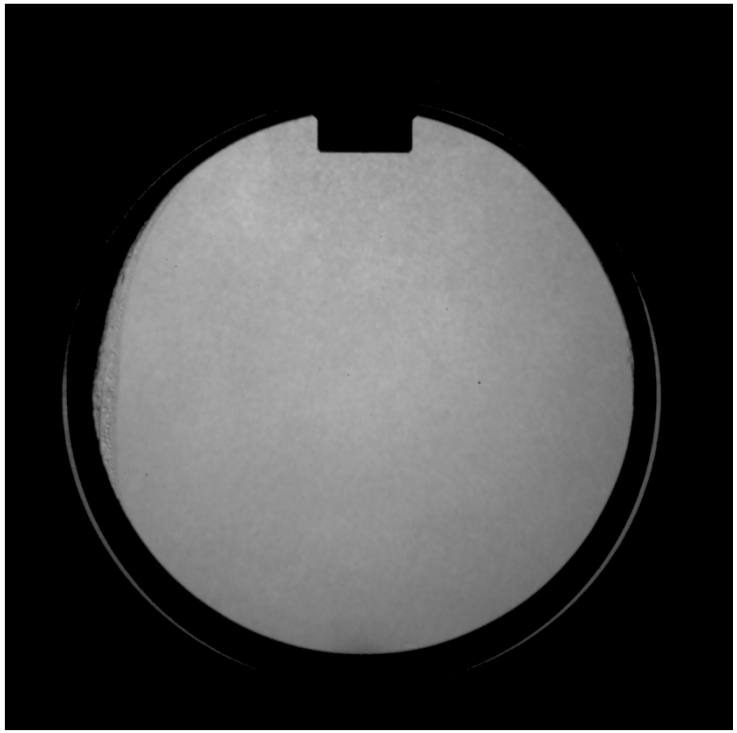




Results LN2 Campaign (I)

- T_{inj} = 82,5 K (±0,6 K)
- p_{inj} = 8 bar
- D_{inj} = 1 mm





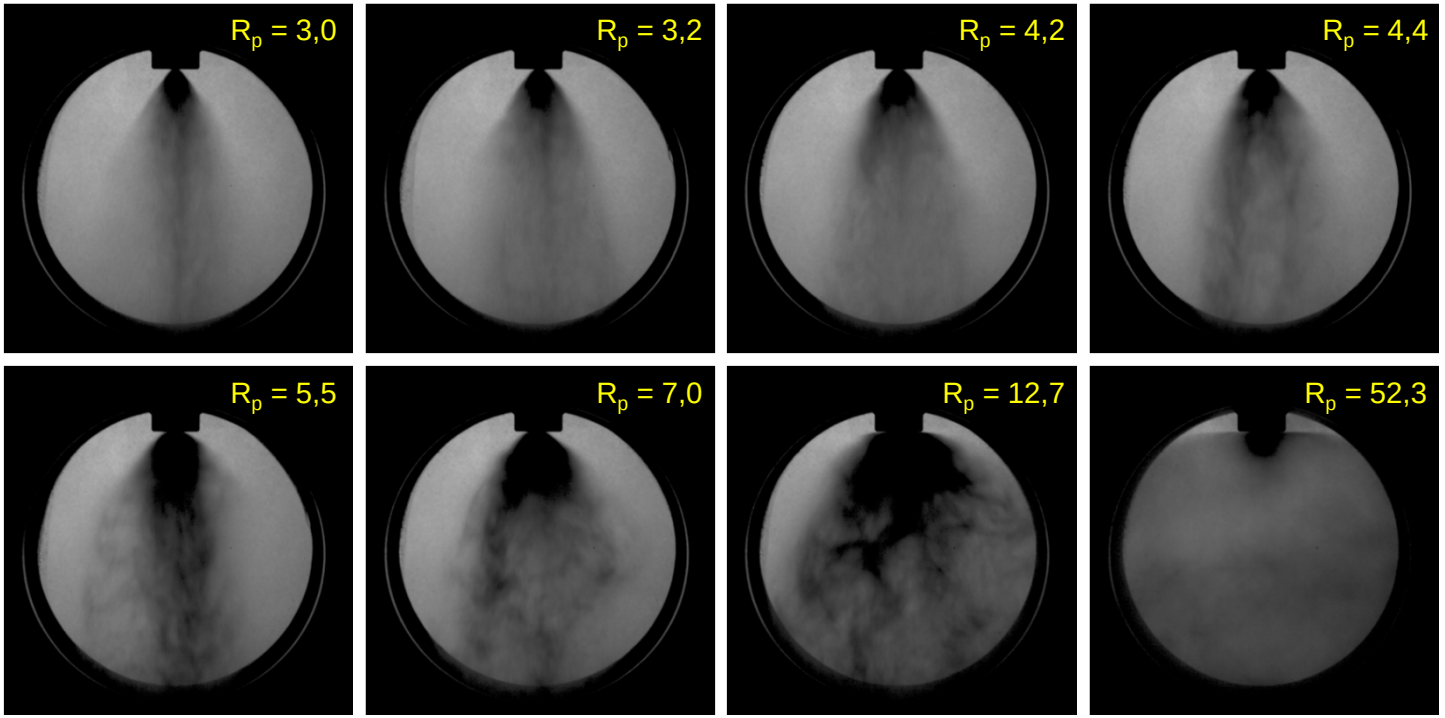
p_c = 600 mbar

p_c = 60 mbar

Results LN2 Campaign (II)

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

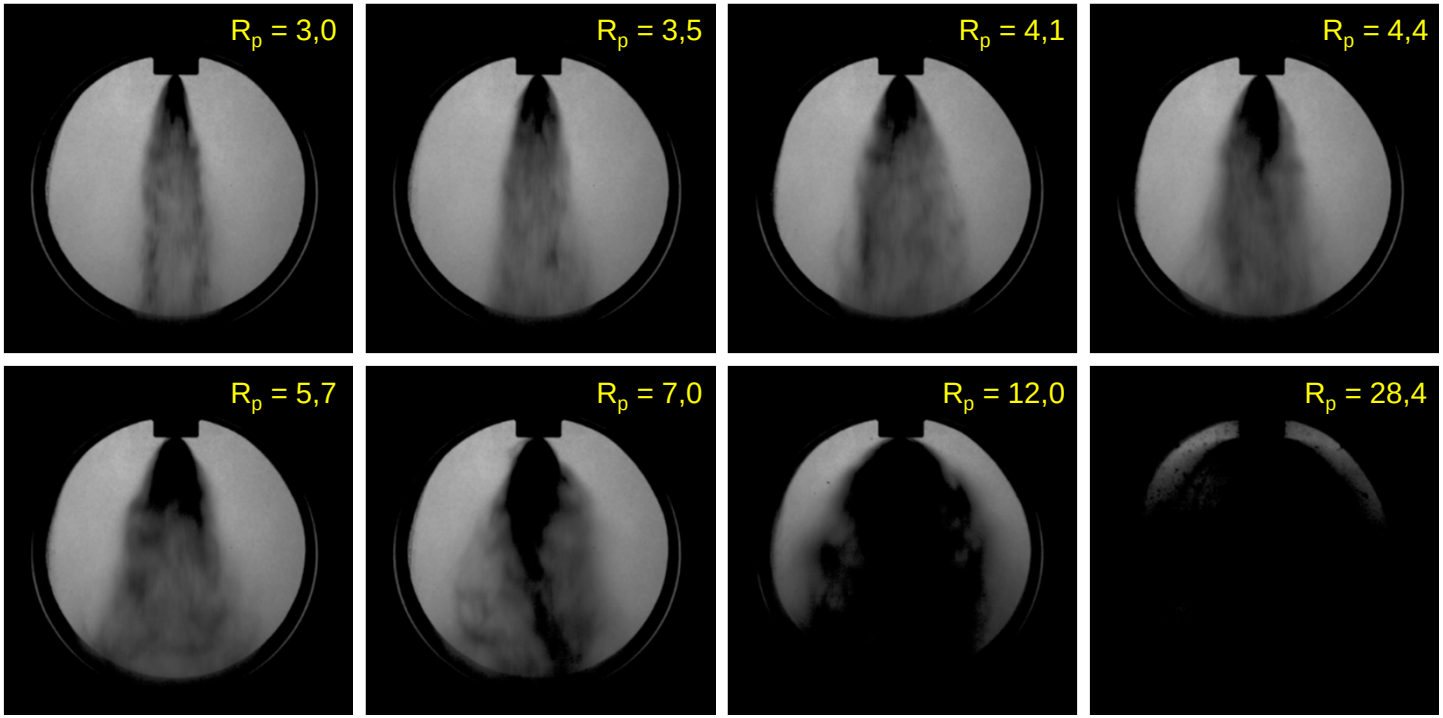
- T_{inj} = 82,5 K (±0,6) K
- p_{inj} = 4 bar
- p_c = 0,037-0,605 bar
- D_{inj} = 1 mm
- High-Speed Shadowgraphy (t = 200 ms)



Results LN2 Campaign (III)

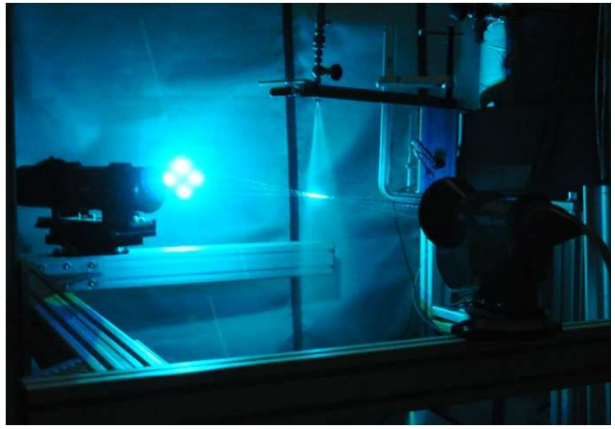
$$R_{\mathrm{p}} = \frac{p_{\mathrm{sat}}(T_{\mathrm{inj}})}{p_{\mathrm{c}}}$$

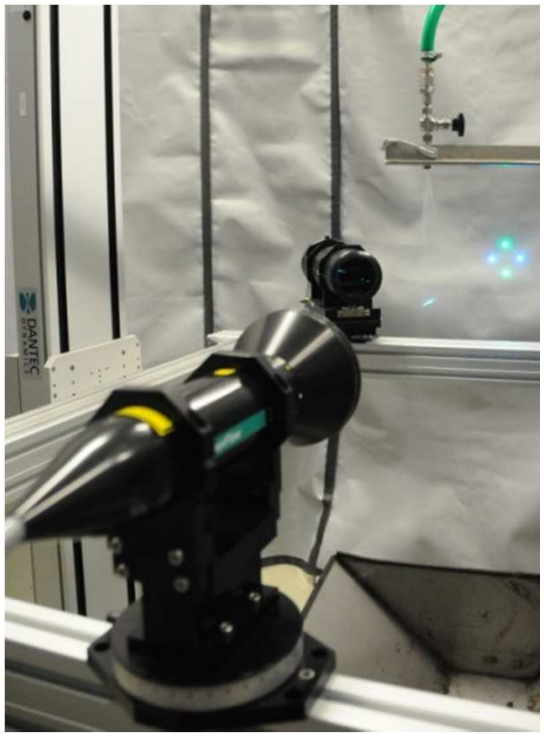
- T_{inj} = 82,4 K (±0,5) K
- p_{inj} = 8 bar
- p_c = 0,059-0,612 bar
- D_{inj} = 1 mm
- High-Speed Shadowgraphy (t = 200 ms)



PDA Setup

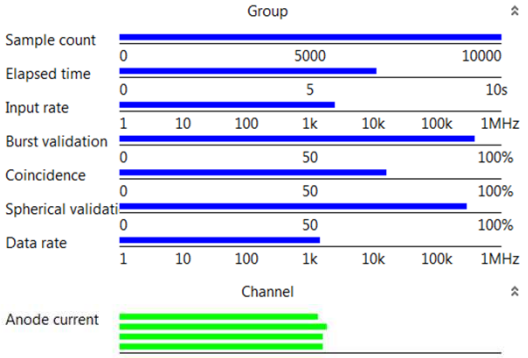
- Dantec High-Dense PDA system
- 2D Dual-PDA
- DPSS 1W Lasers (488 & 514 nm)
- Lenses focal length f = 500 mm
- 2D Traverse system

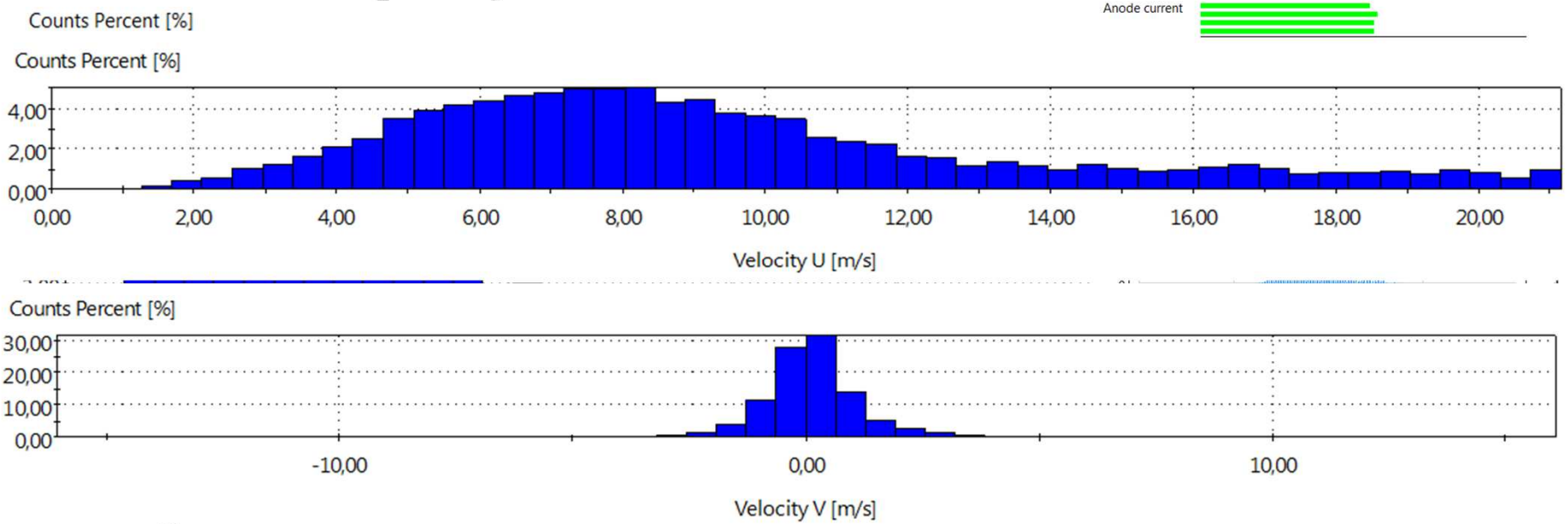




PDA Setup

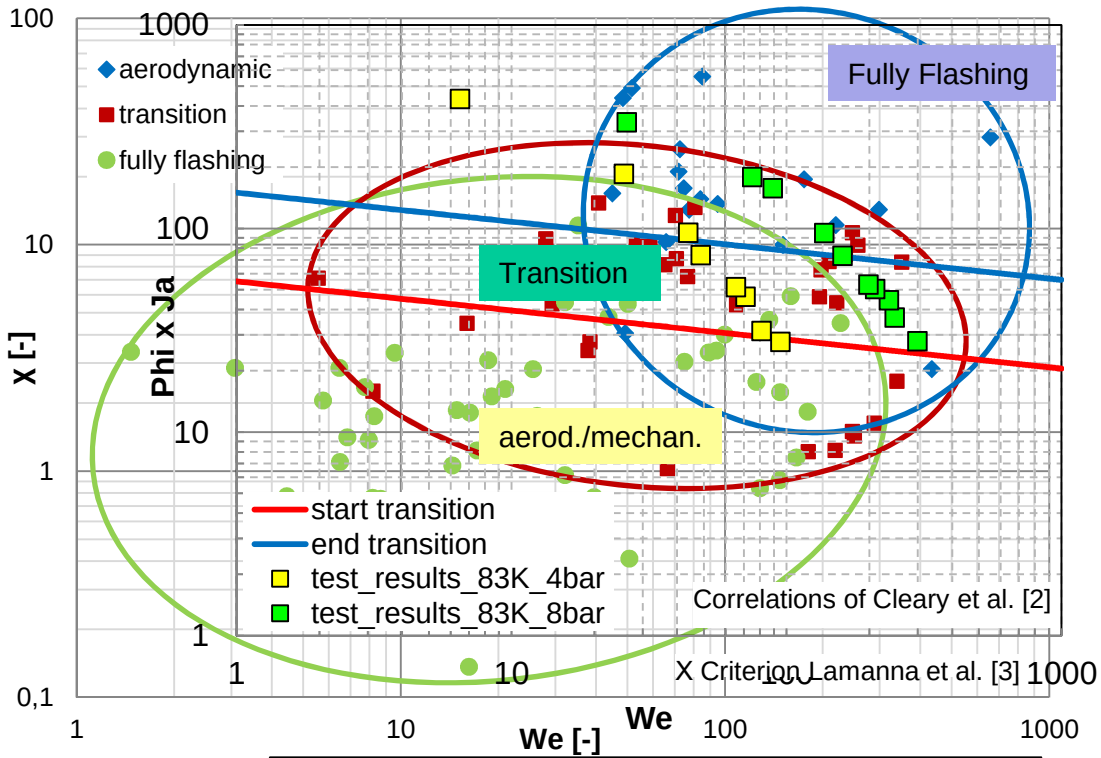
- 1D LDA H_20 free jet
- 2D LDA H_20 free jet
- 1D Fiber-PDA H_20 free jet





Conclusions

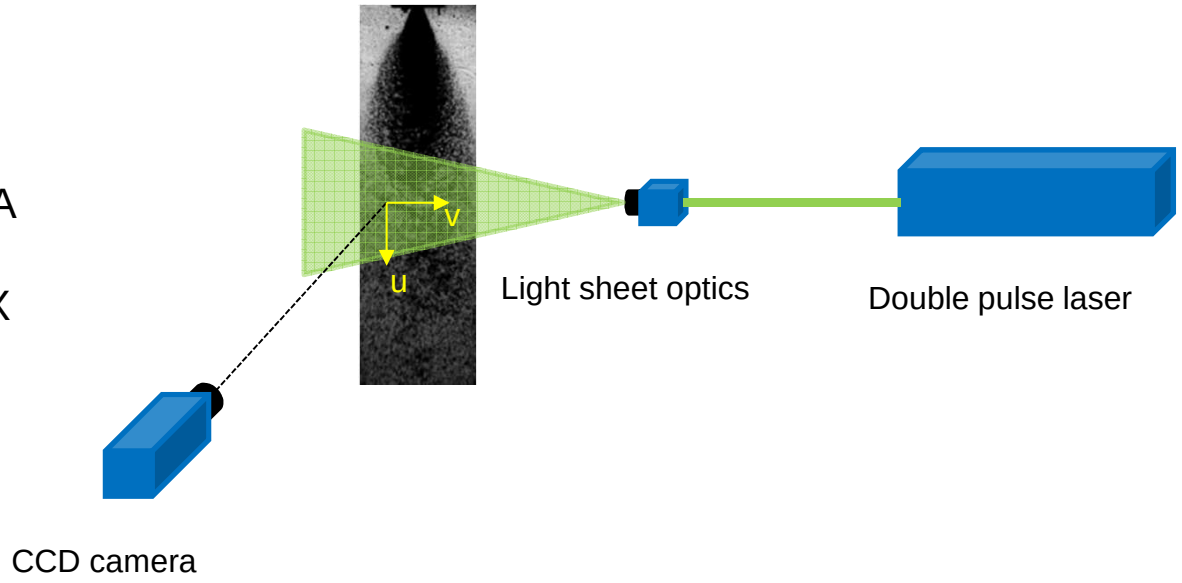
- New cryogenic temperature adjustment and injection system provides sprays with constant injection temperatures T_{inj}
- Decreasing back pressure p_c ➔ increase of R_p and spray angles
- Sprays fit into transition correlation [2]
- Sprays fit into χ criterion [3]



$$\chi = \frac{4}{27}\frac{\Theta^3}{(ln\ R_p)^2} \qquad \Theta = \frac{a_0\sigma}{k_b T_{inj}} \qquad 1 - e^{-2300*\left(\frac{\rho_g}{\rho_L}\right)}$$

Outlook

- Expansion of test matrix:
  - p_c = 1 bar
  - 75 K < T_{inj} < 100 K
- Spray angles
- Droplet size & velocity measurements with PDA of LN2 sprays
- Replacing LN2 with LOX (LCH4)
- PIV



Literature

[1] E. Perez: Ariane 5 User's Manual. Issue 5 Revision 0, July 2008.
[2] V. Cleary, P. Bowen, and H. Witlox: Flashing liquid jets and two-phase droplet dispersion - I. Experiments for derivation of droplet atomization correlations. *J. Hazard. Mater., 142*, pp. 786-796, 2007.
[3] G. Lamanna, H. Kamoun, B. Weigand, C. Manfletti, A. Rees, J. Sender, M. Oschwald, J. Steelant: Flashing Behavior of Rocket Engine Propellants. *Atomization and Sprays*, 25(10), 837–856, 2015