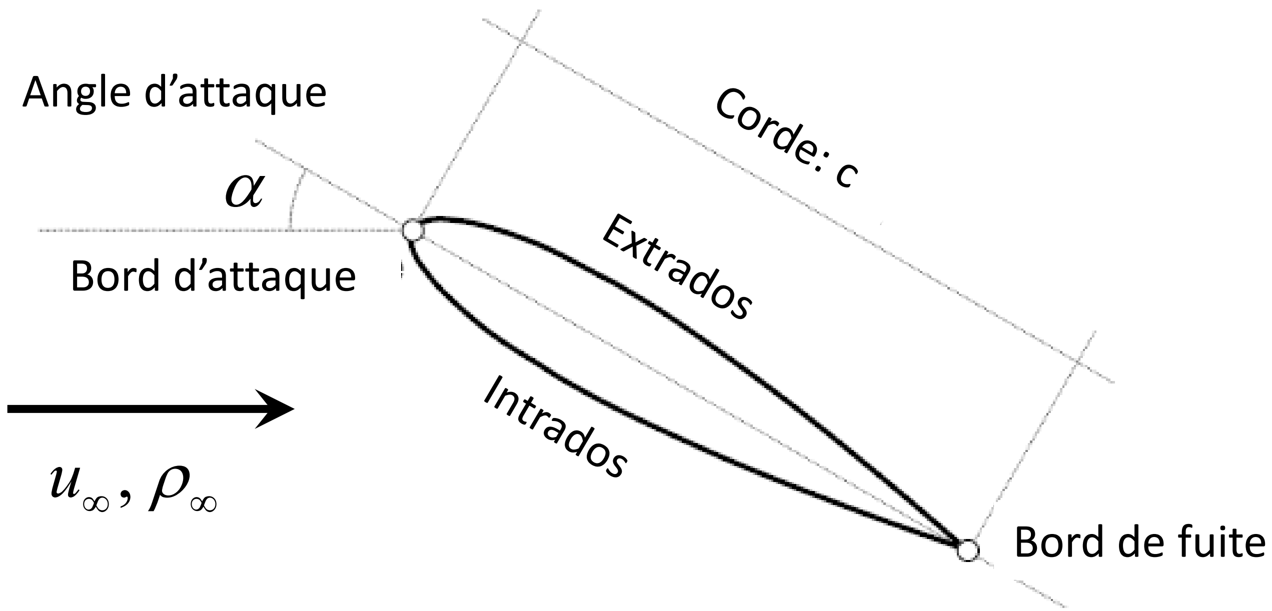
Mécanique des Fluides Compressibles

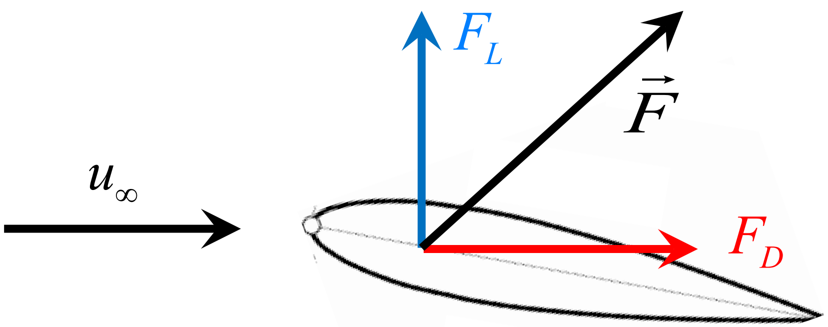
Applications - Ecoulements de Prandtl-Meyer

Dr. Flavio NOCA

Semestre printemps 2024-2025

Profil


Angle d'attaque
α
Bord d'attaque
Corde: c
Extrados
Intrados
u_∞, ρ_∞
Bord de fuite



$$M = \frac{u}{a}$$

$$a^2 = \frac{\gamma p}{\rho}$$

Force de portance F_L **(par unité d'envergure)**

La force de portance est la composante de la force $\vec{F}$ agissant sur le profil et orientée perpendiculairement à l'écoulement incident (L = lift)

Force de traînée F_D **(par unité d'envergure)**

La force de traînée est la composante de la force $\vec{F}$ agissant sur le profil et orientée tangentiellement à l'écoulement incident (D = drag)

Coefficient de portance c_L

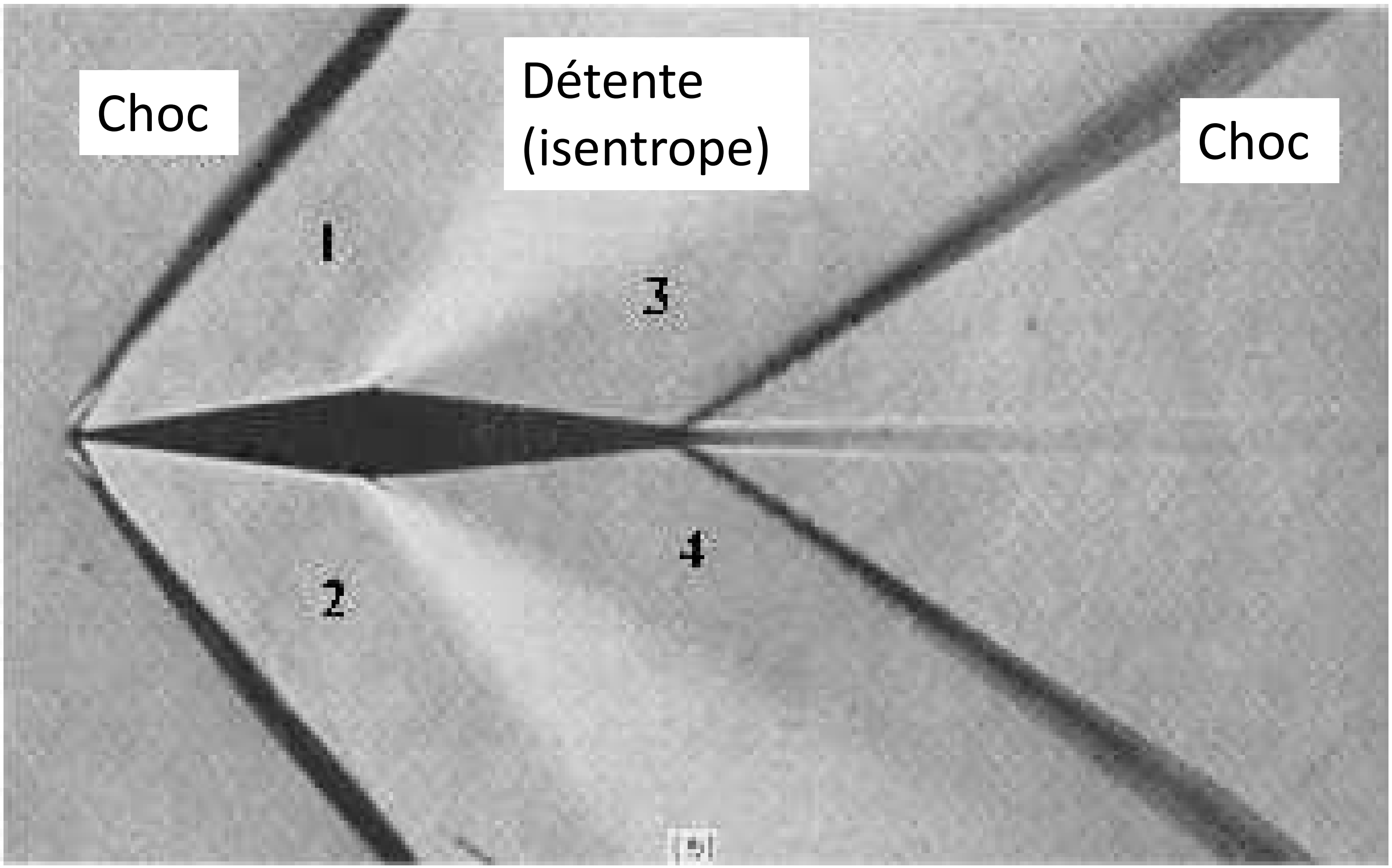
(de section de profil)

$$c_L = \frac{F_L}{\frac{1}{2}\rho_\infty u_\infty^2 c} = \frac{F_L}{\frac{1}{2}\gamma p_\infty M_\infty^2 c}$$

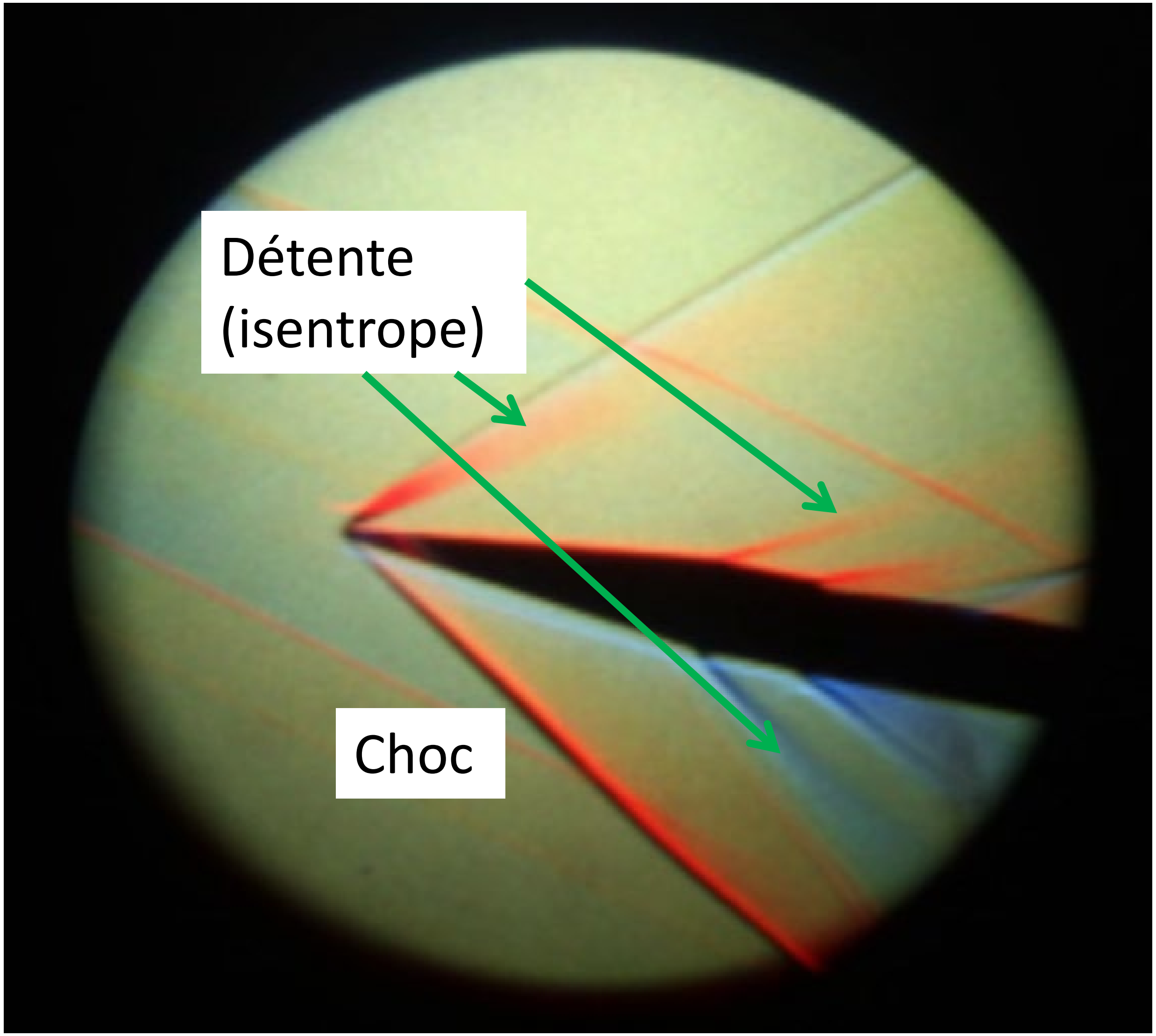
Coefficient de traînée c_D

(de section de profil)

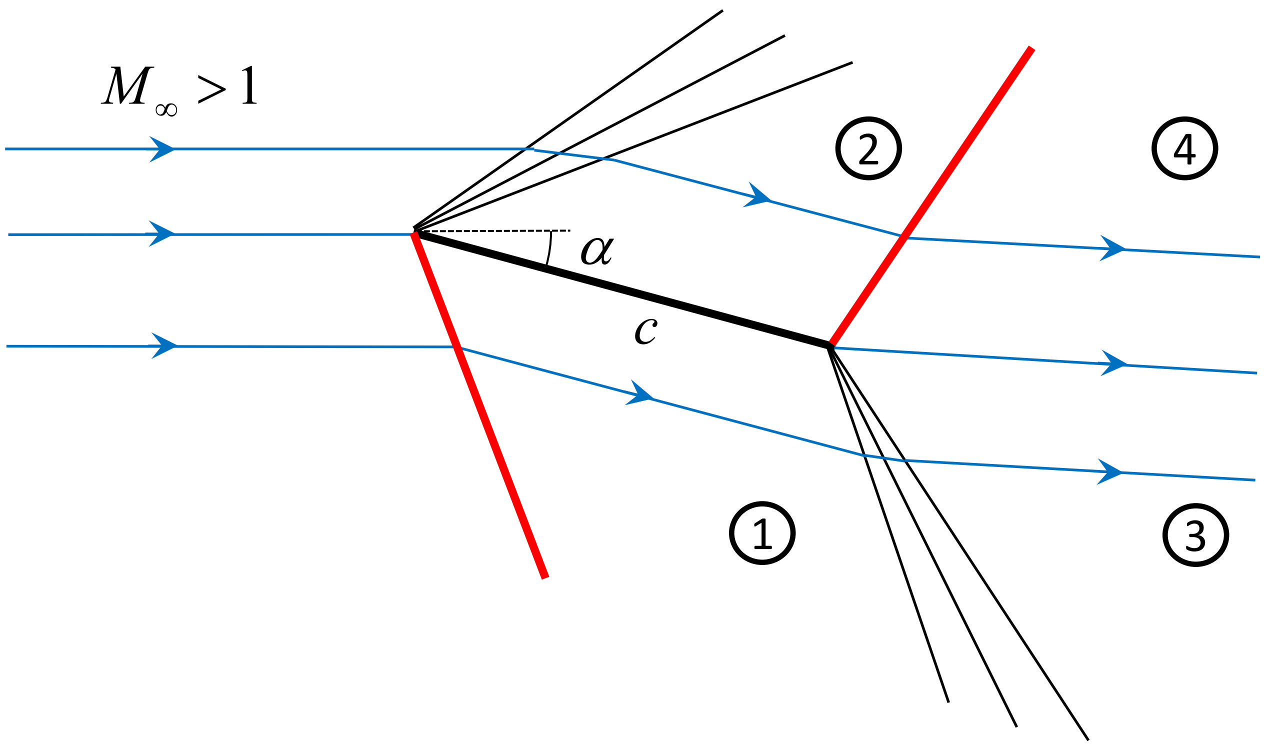
$$c_D = \frac{F_D}{\frac{1}{2}\rho_\infty u_\infty^2 c} = \frac{F_D}{\frac{1}{2}\gamma p_\infty M_\infty^2 c}$$


Choc
Détente
(isentrope)
Choc
1
3
2
4

Forces aérodynamiques sur des profils

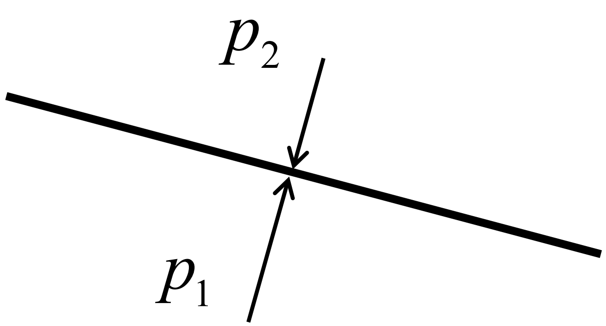

Détente
(isentrope)
Choc

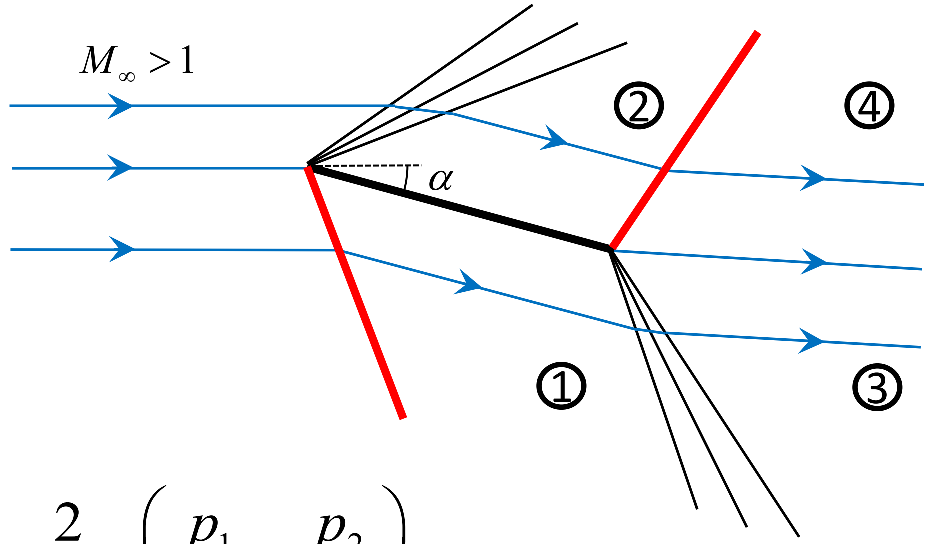
Ecoulement autour d'une plaque plane



Ecoulement autour d'une plaque plane

Hypothèse: Ecoulement supersonique partout





$$F_L = (p_1 - p_2) c \cos\alpha \qquad c_L = \frac{2}{\gamma M_\infty^2}\left(\frac{p_1}{p_\infty} - \frac{p_2}{p_\infty}\right)\cos\alpha$$

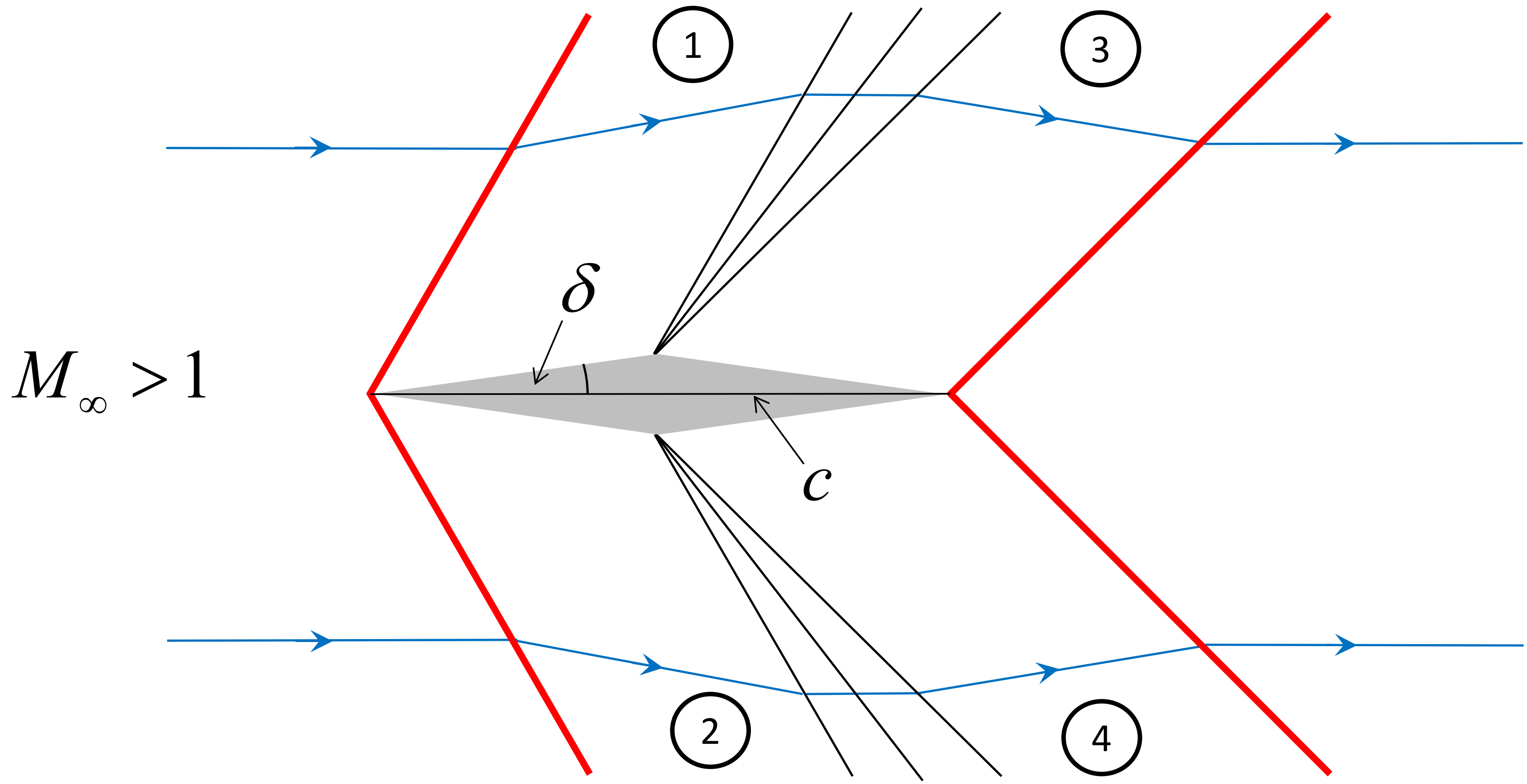
$$F_D = (p_1 - p_2) c \sin\alpha \qquad \boxed{c_D = c_L \tan\alpha}$$

$$c_L = \frac{F_L}{\frac{1}{2}\gamma p_\infty M_\infty^2 c}$$

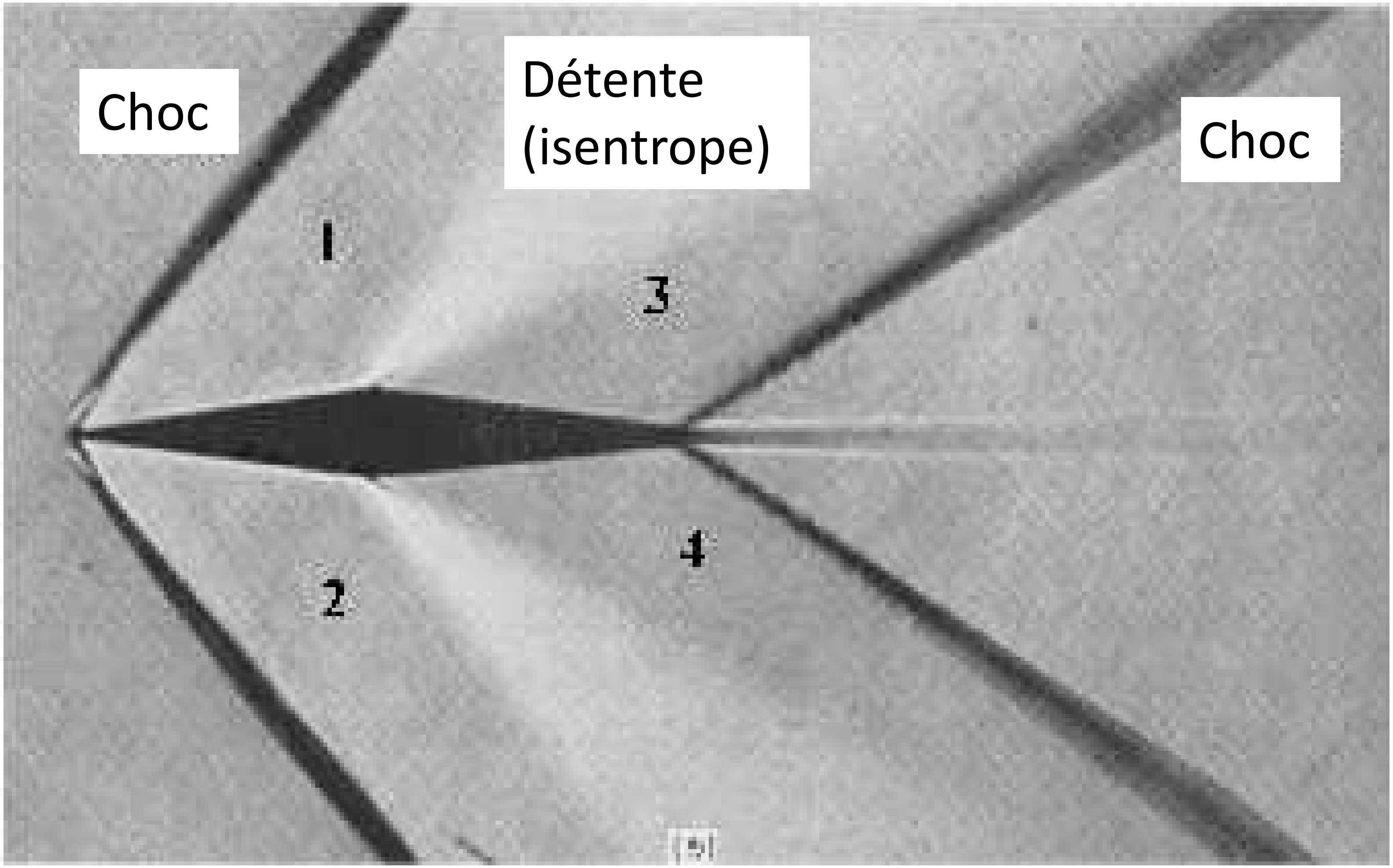
$$c_D = \frac{F_D}{\frac{1}{2}\gamma p_\infty M_\infty^2 c}$$

Traînée d'onde due à la portance

Hypothèse: Ecoulement supersonique partout

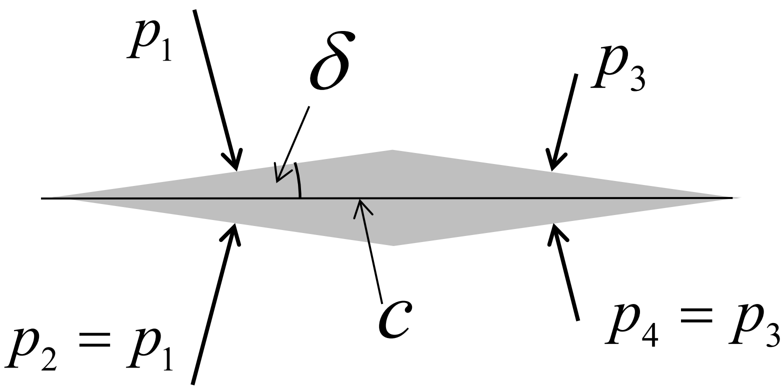


Ecoulement autour d'un profil en losange



Ecoulement autour d'un profil en losange

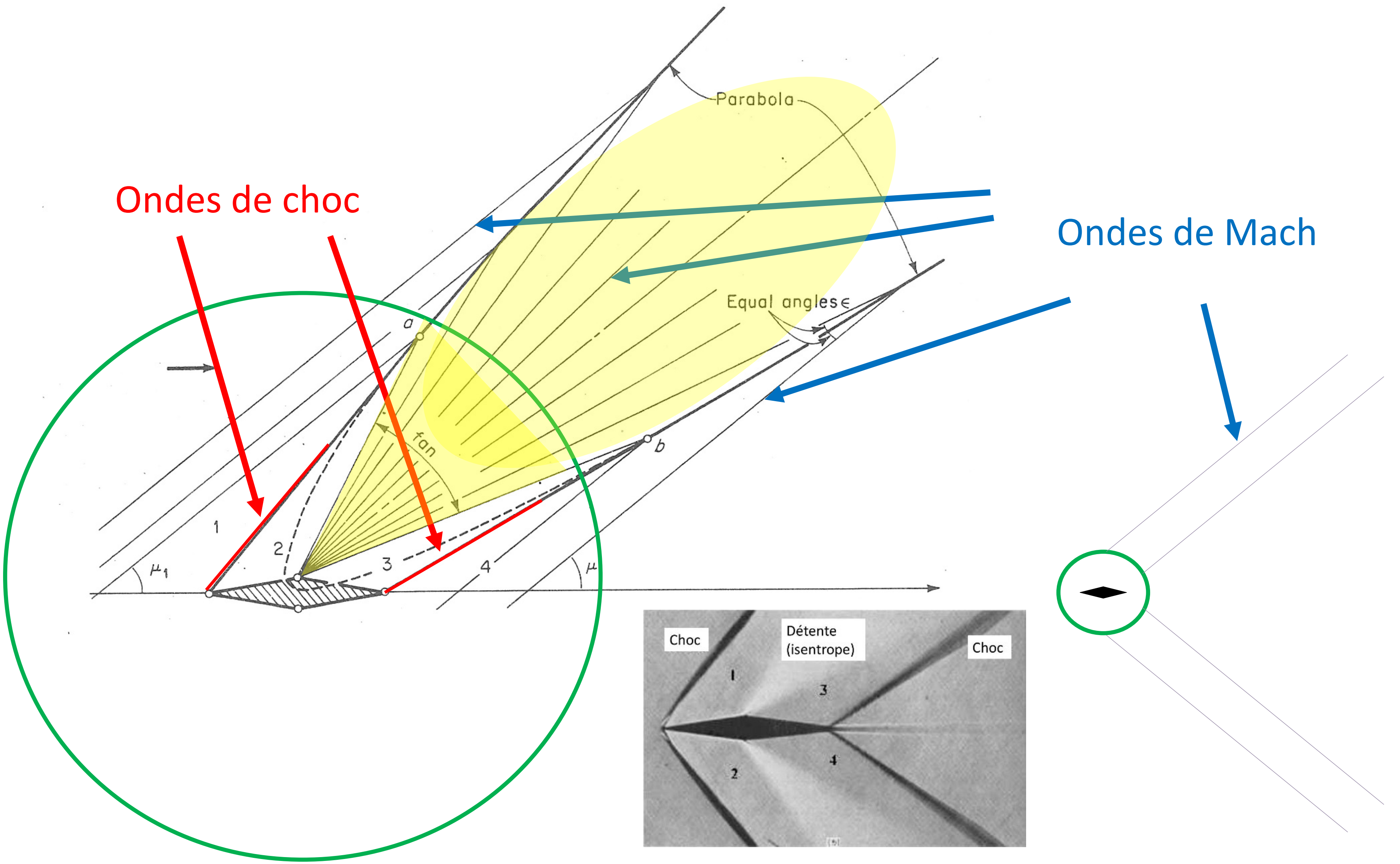
$$F_{D,1} = F_{D,2} = p_1 \frac{c/2}{\cos\delta}\sin\delta \qquad F_{D,3} = F_{D,4} = -p_3 \frac{c/2}{\cos\delta}\sin\delta$$



$$F_D = \sum_{i=1}^{i=4} F_{D,i} = c(p_1 - p_3)\tan\delta$$

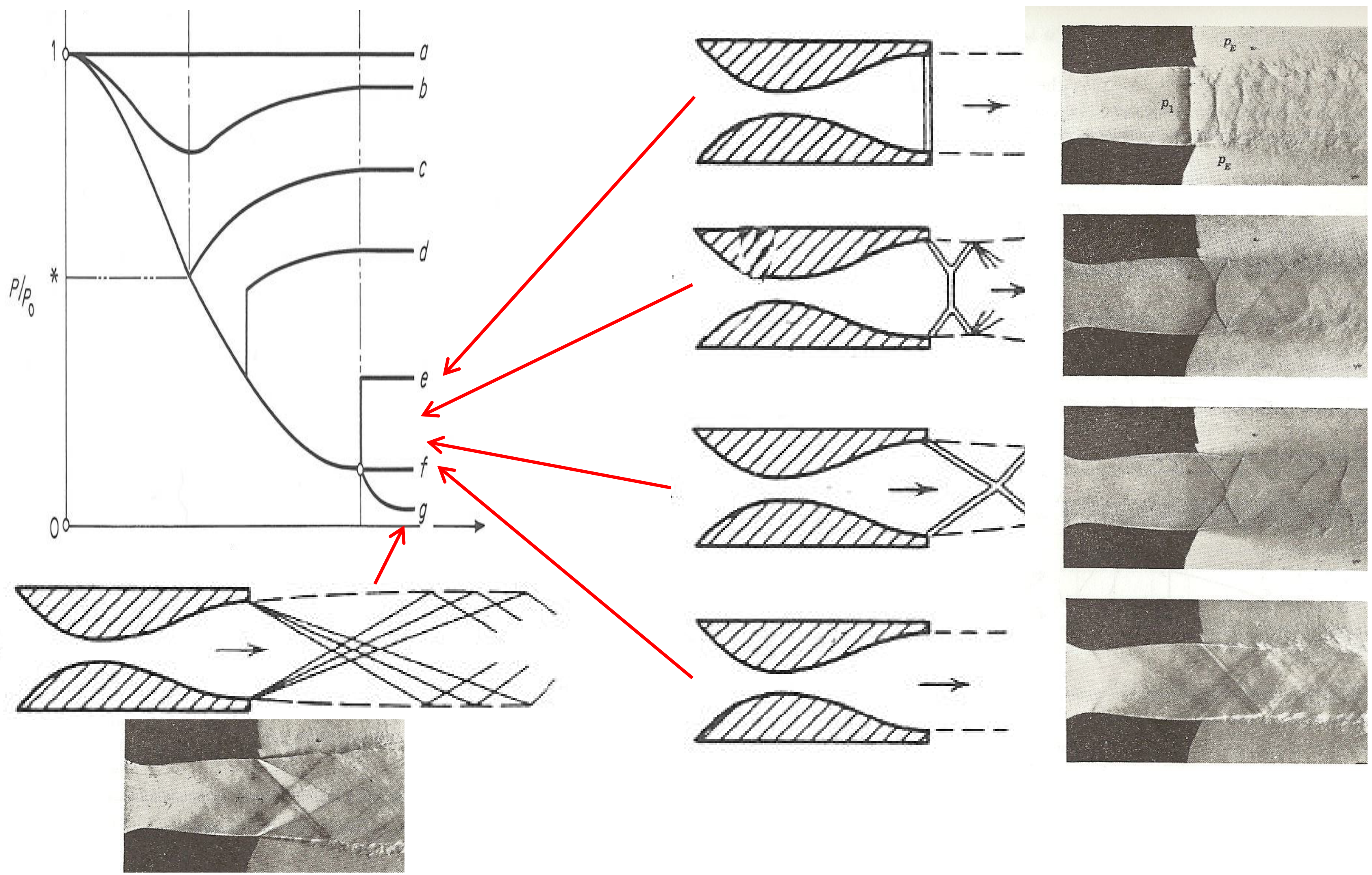
$$c_D = \frac{2}{\gamma M_\infty^2}\left(\frac{p_1}{p_\infty} - \frac{p_3}{p_\infty}\right)\tan\delta$$

Traînée d'onde due à l'épaisseur



Ondes de choc
Ondes de Mach
Parabola
Equal angles ϵ
fan
a
b
1
2
3
4
Choc
Détente
(isentrope)
Choc

Tuyère Convergente - Divergente



Ecoulement sous-détendu (underexpanded)

Sillages de tuyères supersoniques

«Long March 2F» – Shenzhou 5

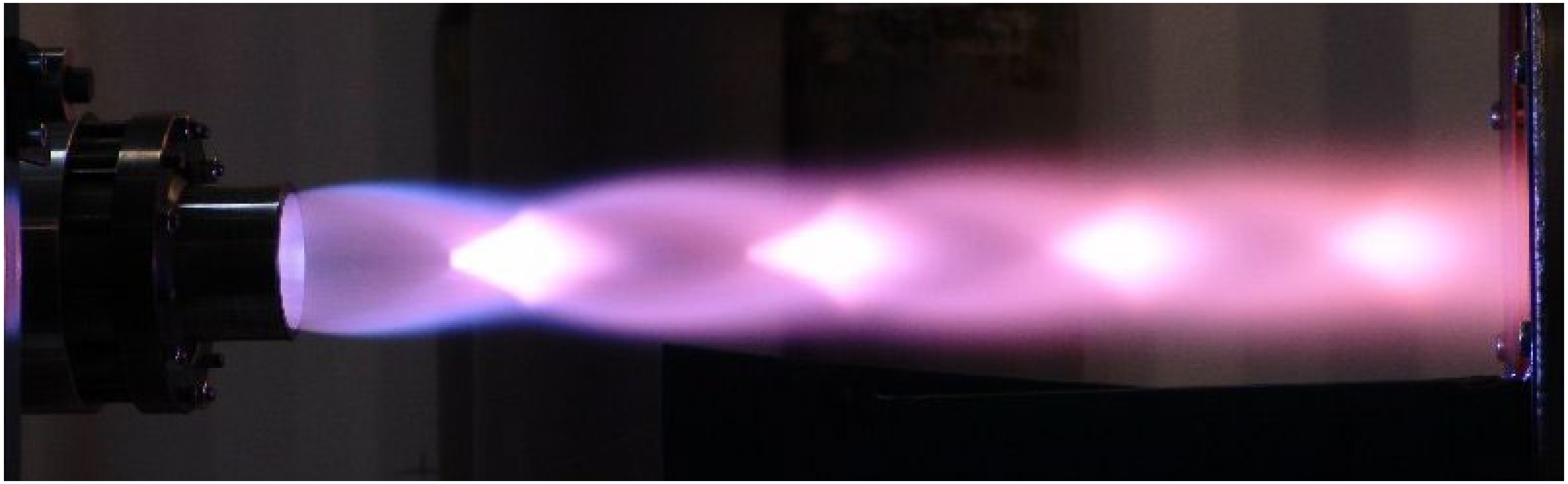
N_2O_4 : peroxide d'azote

UDMH : unsymmetrical dimethyl hydrazine

Sillages de tuyères supersoniques

Swiss Propulsion Laboratory, www.spl.ch

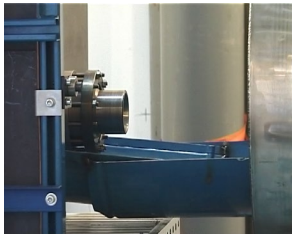
Poussée: 2’500 N (LOX + HC)



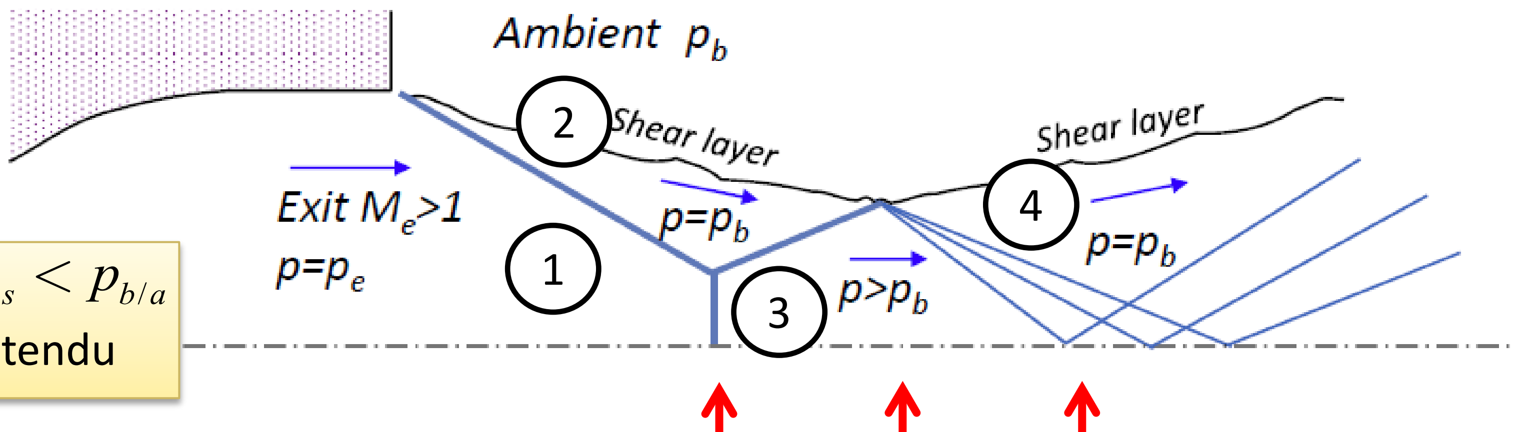
Pression de sortie: 0,7 bar < p_{atm} (sur-détendu)

$$p_{e/s} < p_{b/a}$$

sur-détendu

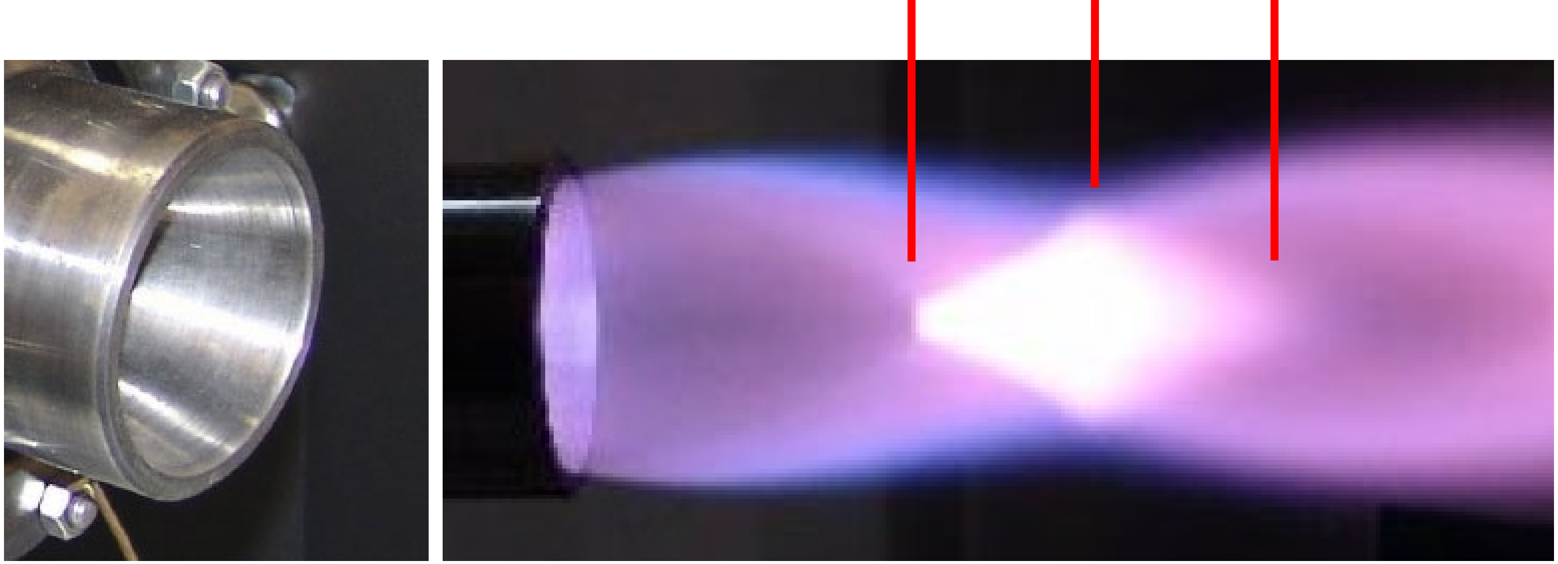


Sortie de tuyère avec écoulement sur-détendu (overexpanded)



$$p_1 = p_{e/s} < p_{b/a}$$

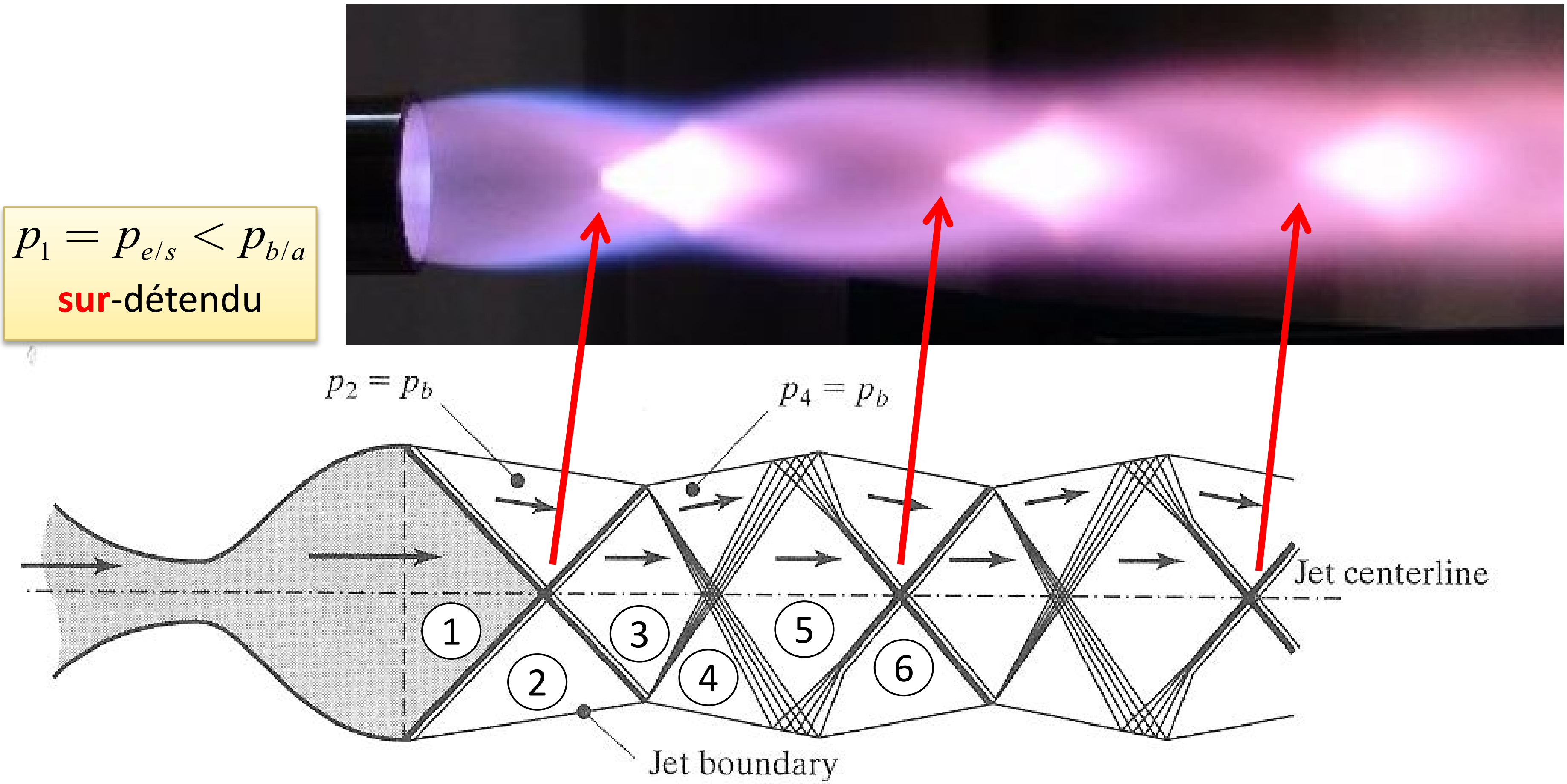
sur-détendu



Sortie de tuyère avec écoulement sur-détendu (overexpanded)

$p_1 = p_{e/s} < p_{b/a}$

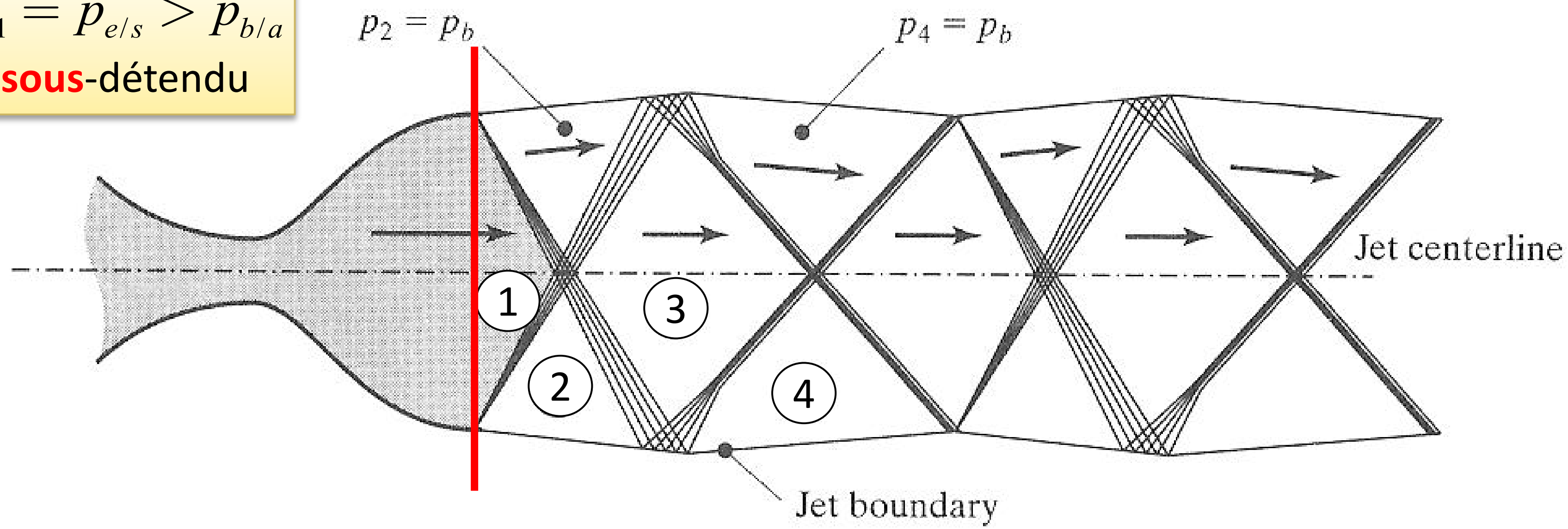
sur-détendu



Comparaison: sous-détendu & sur-détendu (underexpanded & overexpanded)

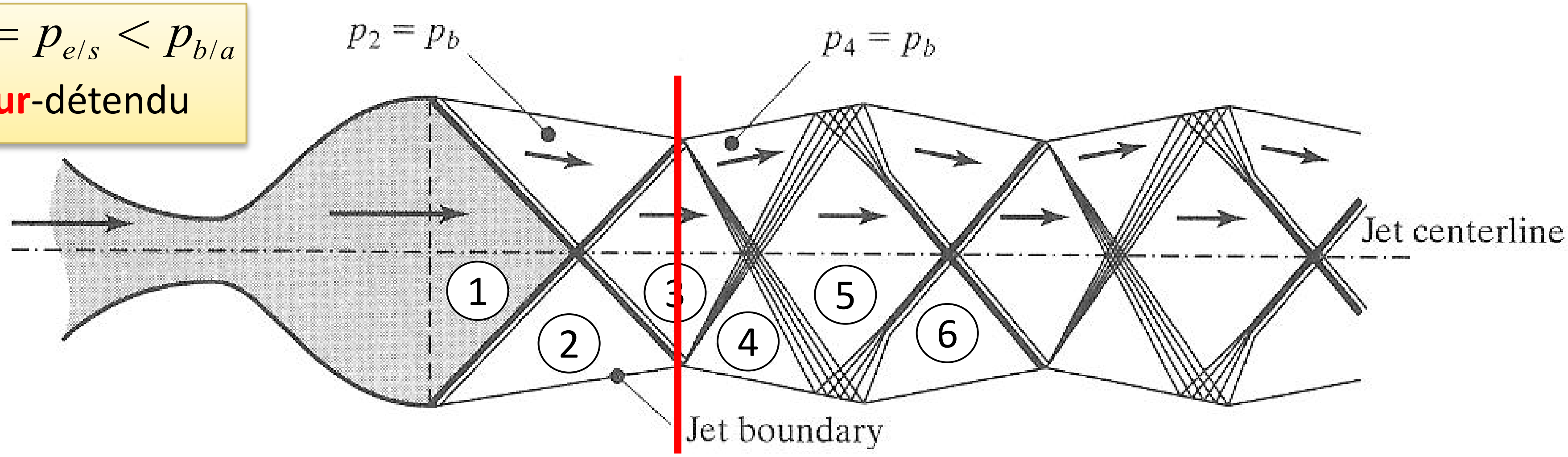
$p_1 = p_{e/s} > p_{b/a}$

sous-détendu

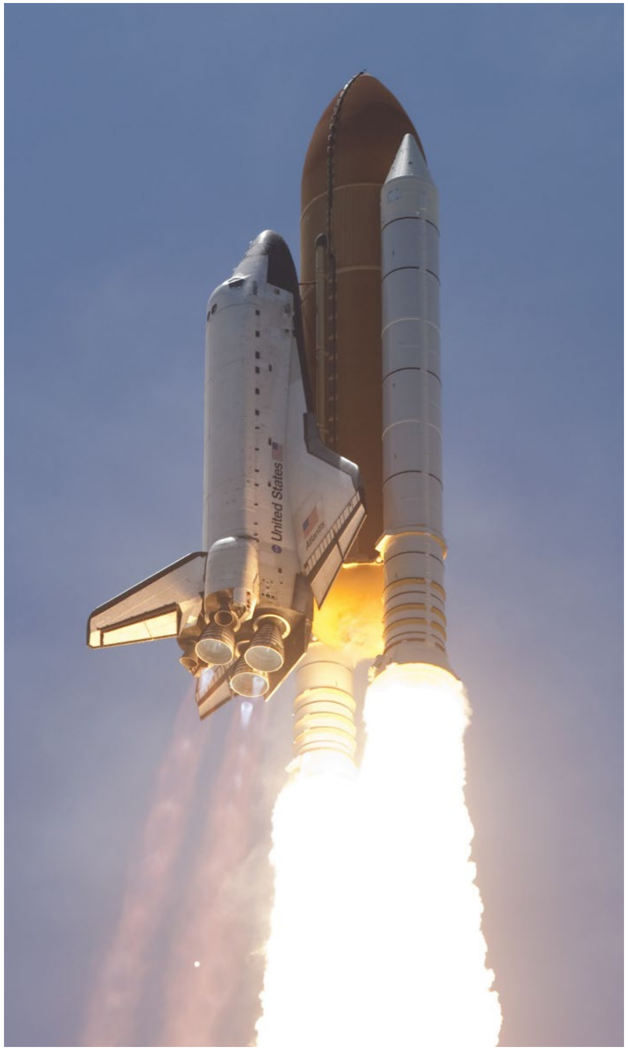


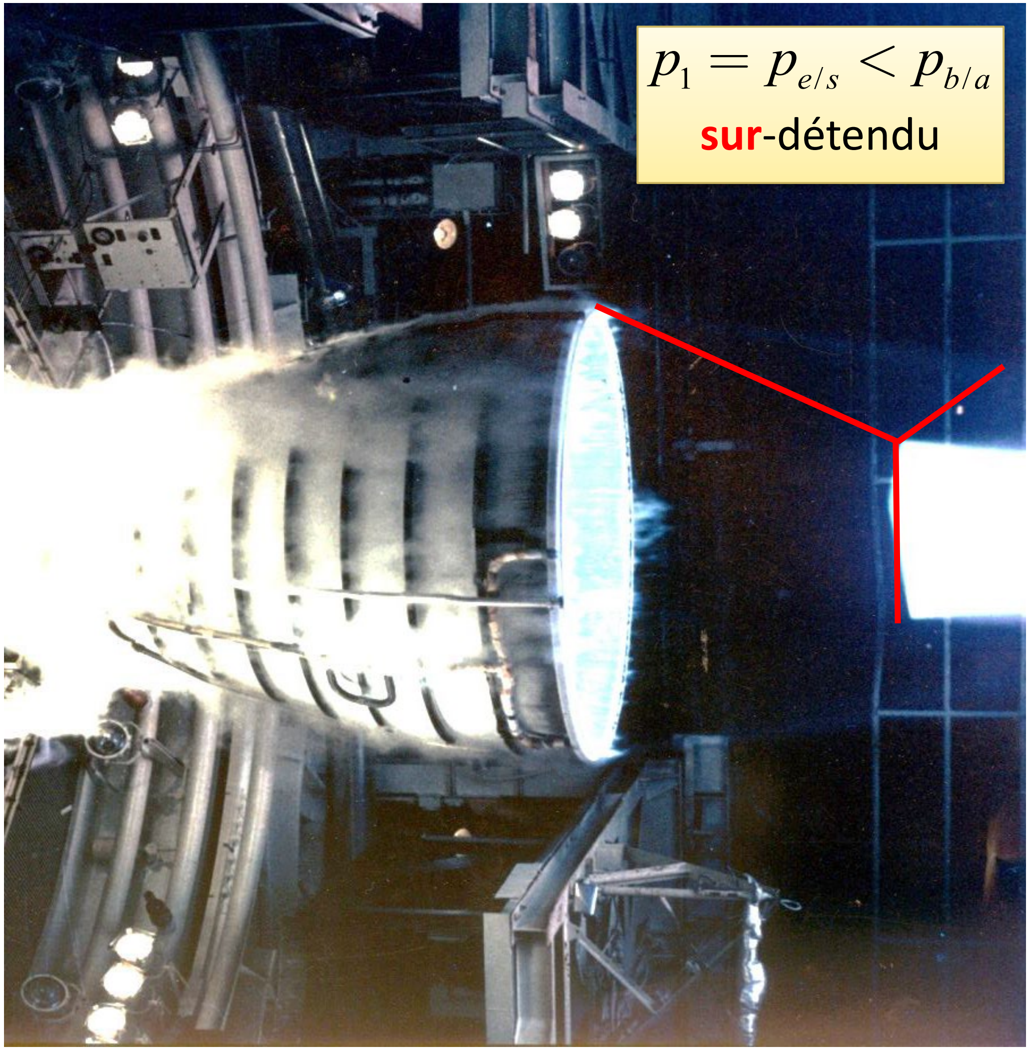
$p_1 = p_{e/s} < p_{b/a}$

sur-détendu



Sortie de tuyère avec écoulement sur-détendu (overexpanded)

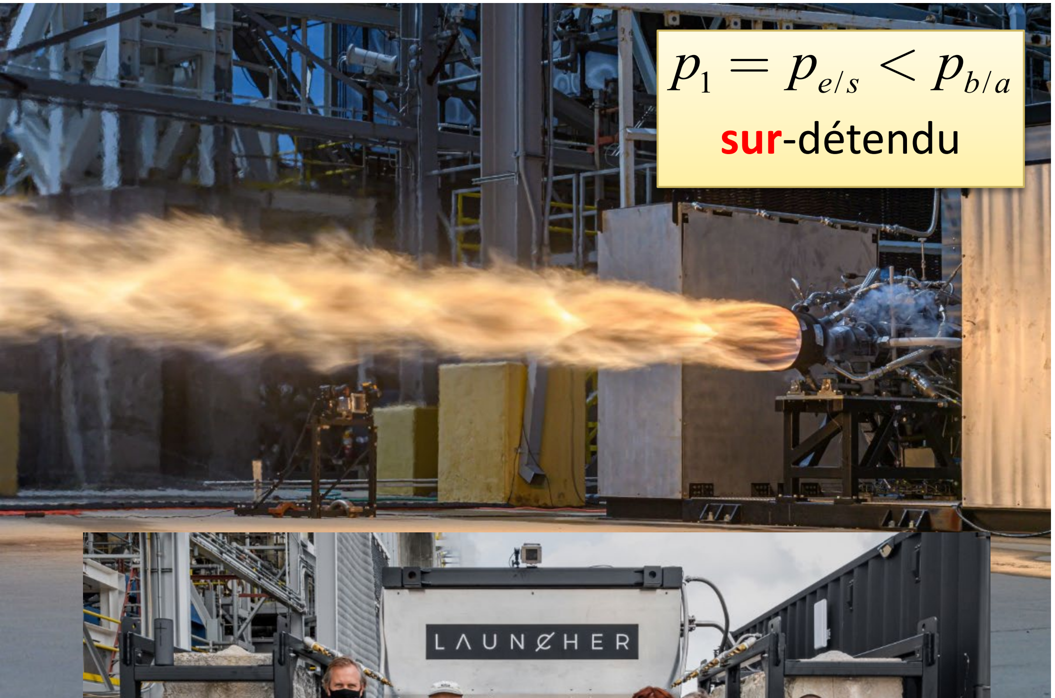




$$p_1 = p_{e/s} < p_{b/a}$$

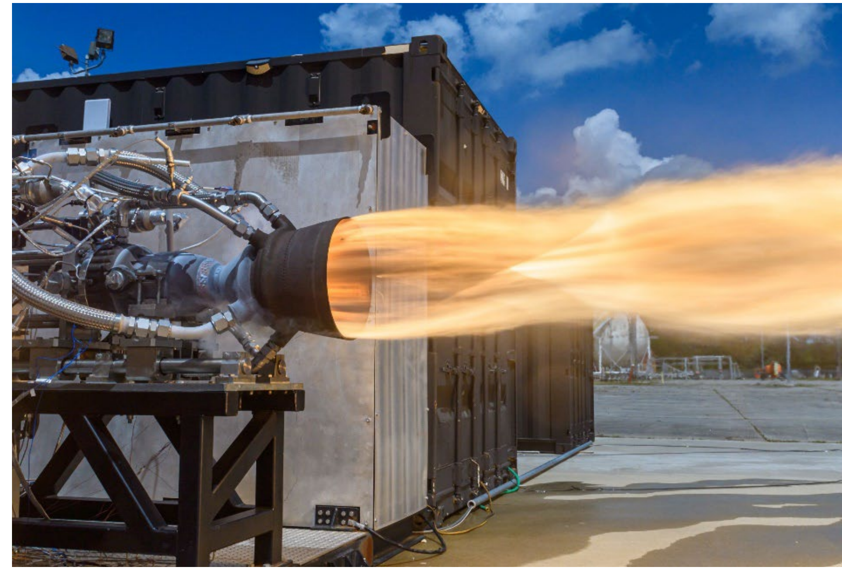
sur-détendu

LAUNCHER (3D printed) RP1 (Kerosene) + LOX (2021)



$$p_1 = p_{e/s} < p_{b/a}$$

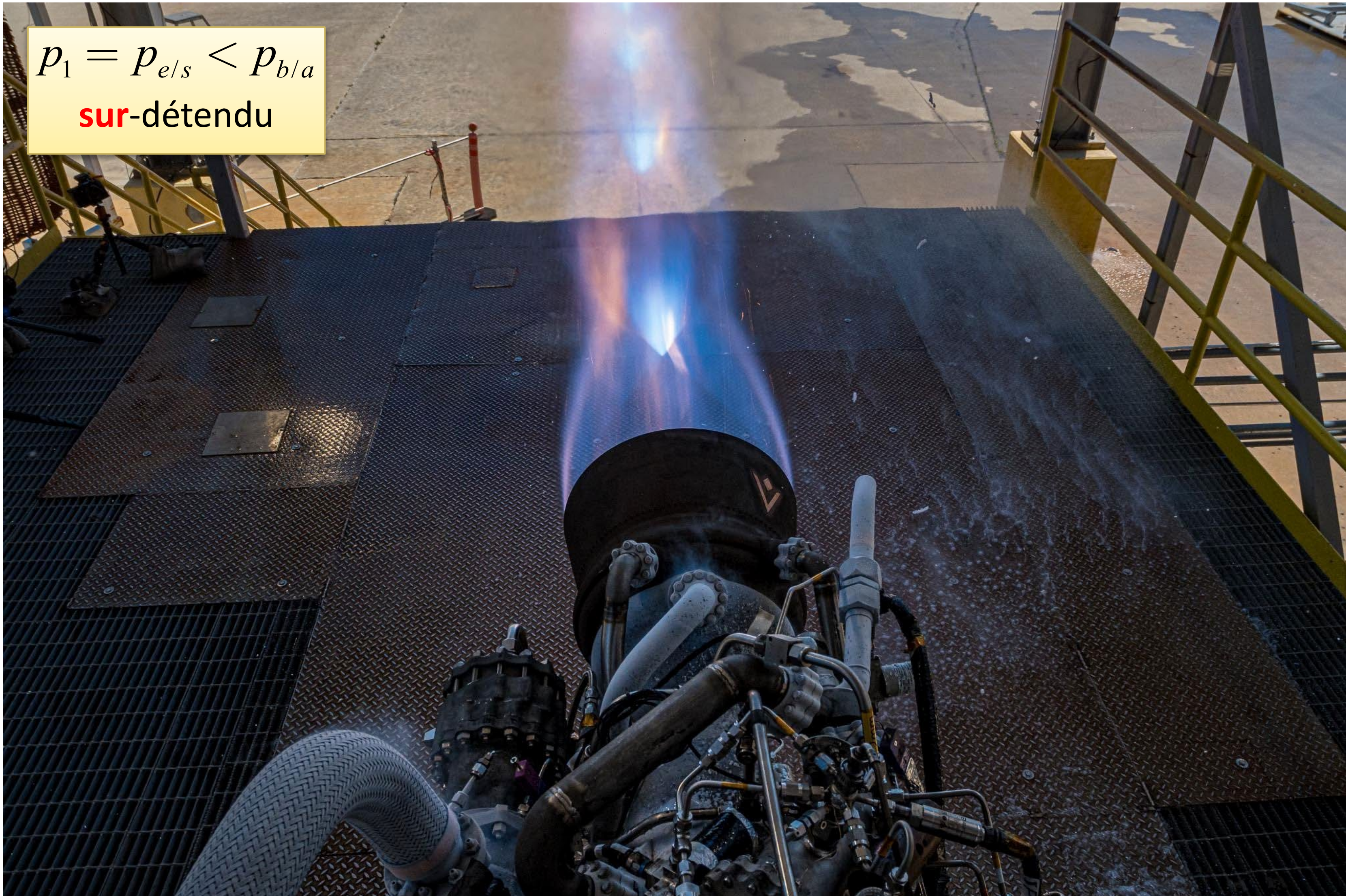
sur-détendu



LAUNCHER RP1 (Kerosene) + LOX (2024)

$$p_1 = p_{e/s} < p_{b/a}$$

sur-détendu



Relativity Space
Terran 1
3D printed
(23 Mars 2023)

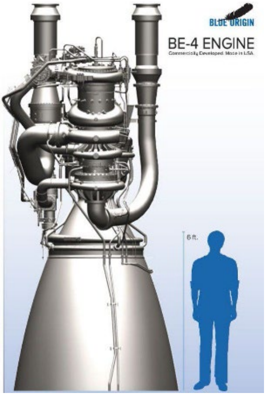
Methane + LOX

$$p_1 = p_{e/s} < p_{b/a}$$
sur-détendu

SpaceX Starship CH4 + LOX (Dec 7 2023)

$$p_1 = p_{e/s} < p_{b/a}$$

sur-détendu

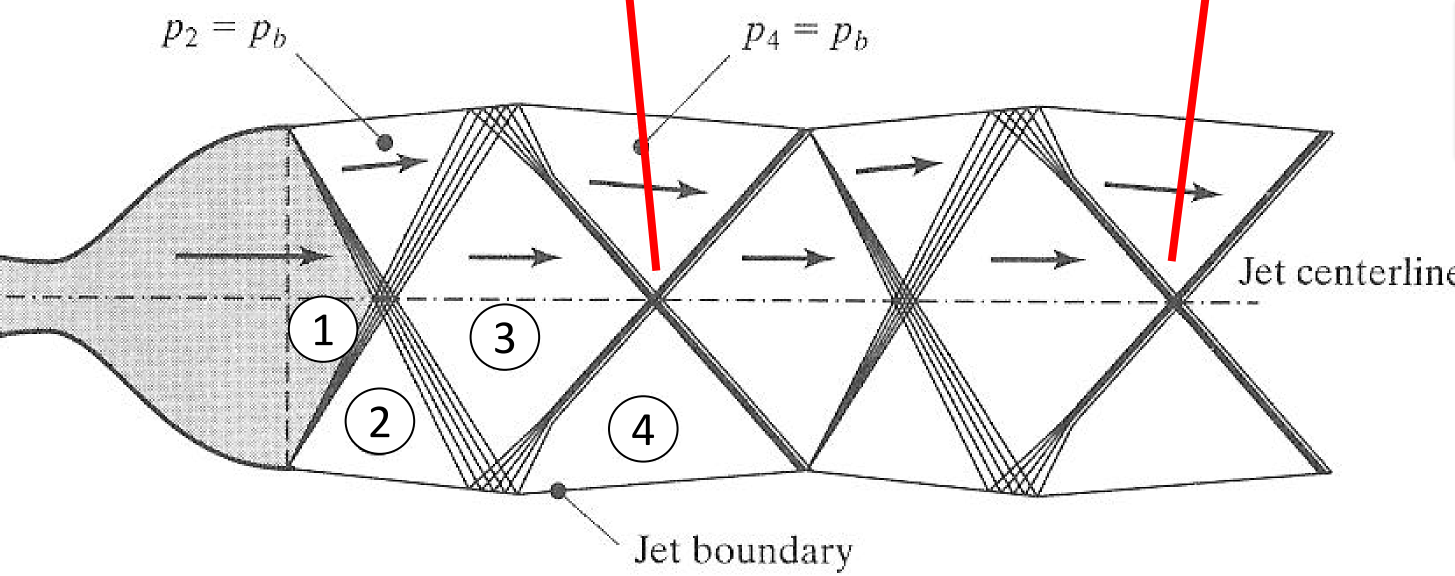


$$p_1 = p_{e/s} < p_{b/a}$$

sur-détendu

Imagerie Schlieren de jets sous-détendus

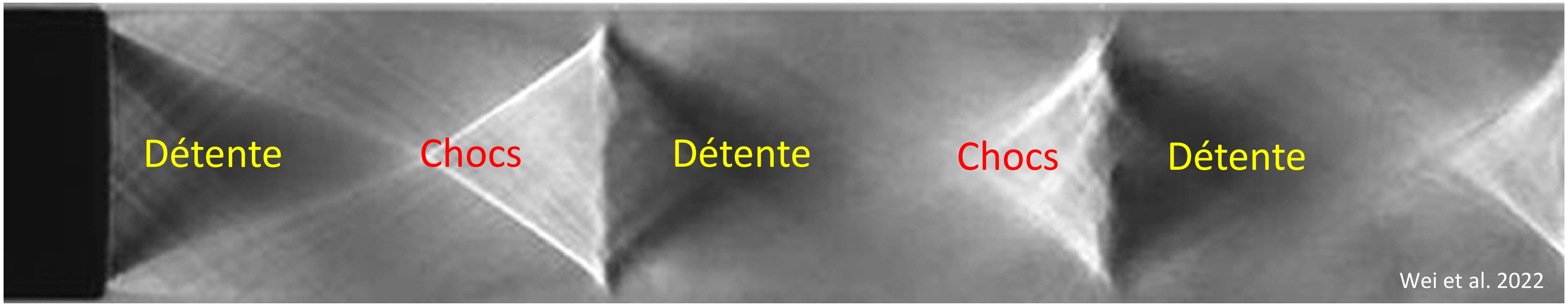
L'imagerie Schlieren visualise des **gradients** de densité

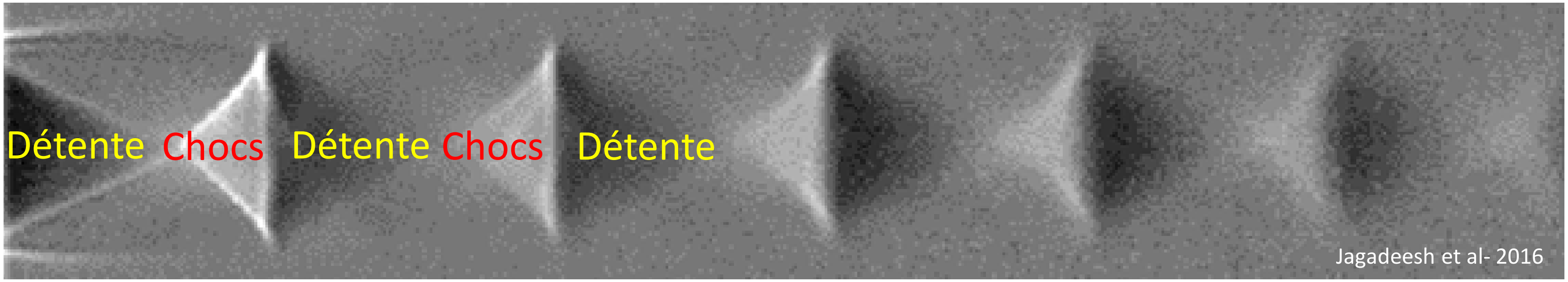


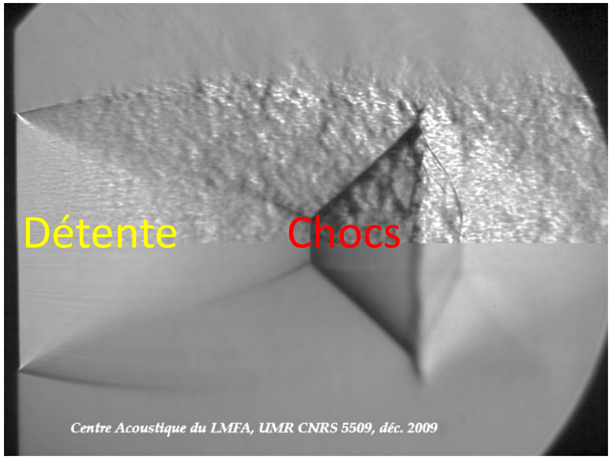
$$p_1 = p_{e/s} > p_{b/a}$$

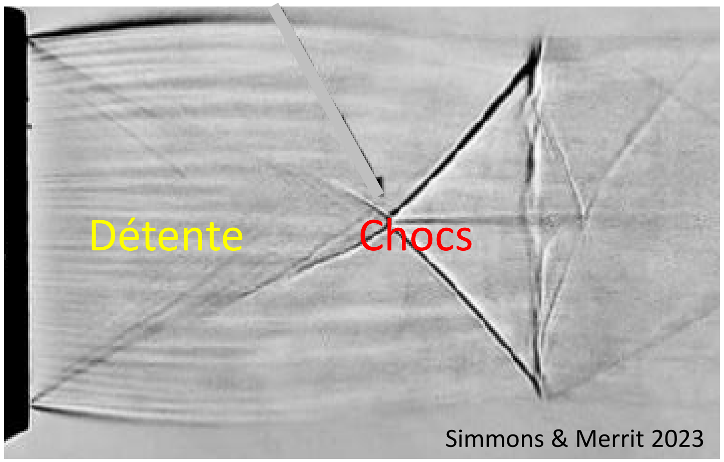
sous-détendu

Imagerie Schlieren de jets sous-détendus





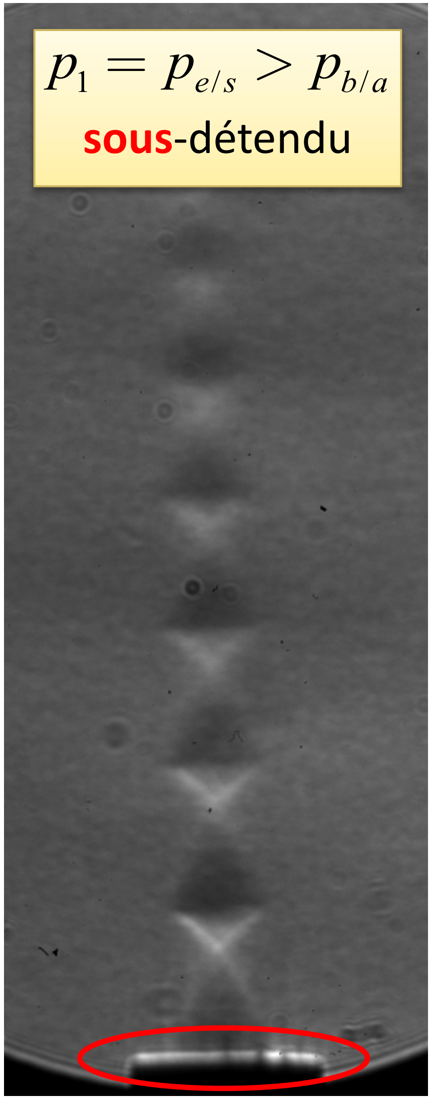




$$p_1 = p_{e/s} > p_{b/a}$$

sous-détendu

Buse de prophylaxie dentaire – sous-détendue

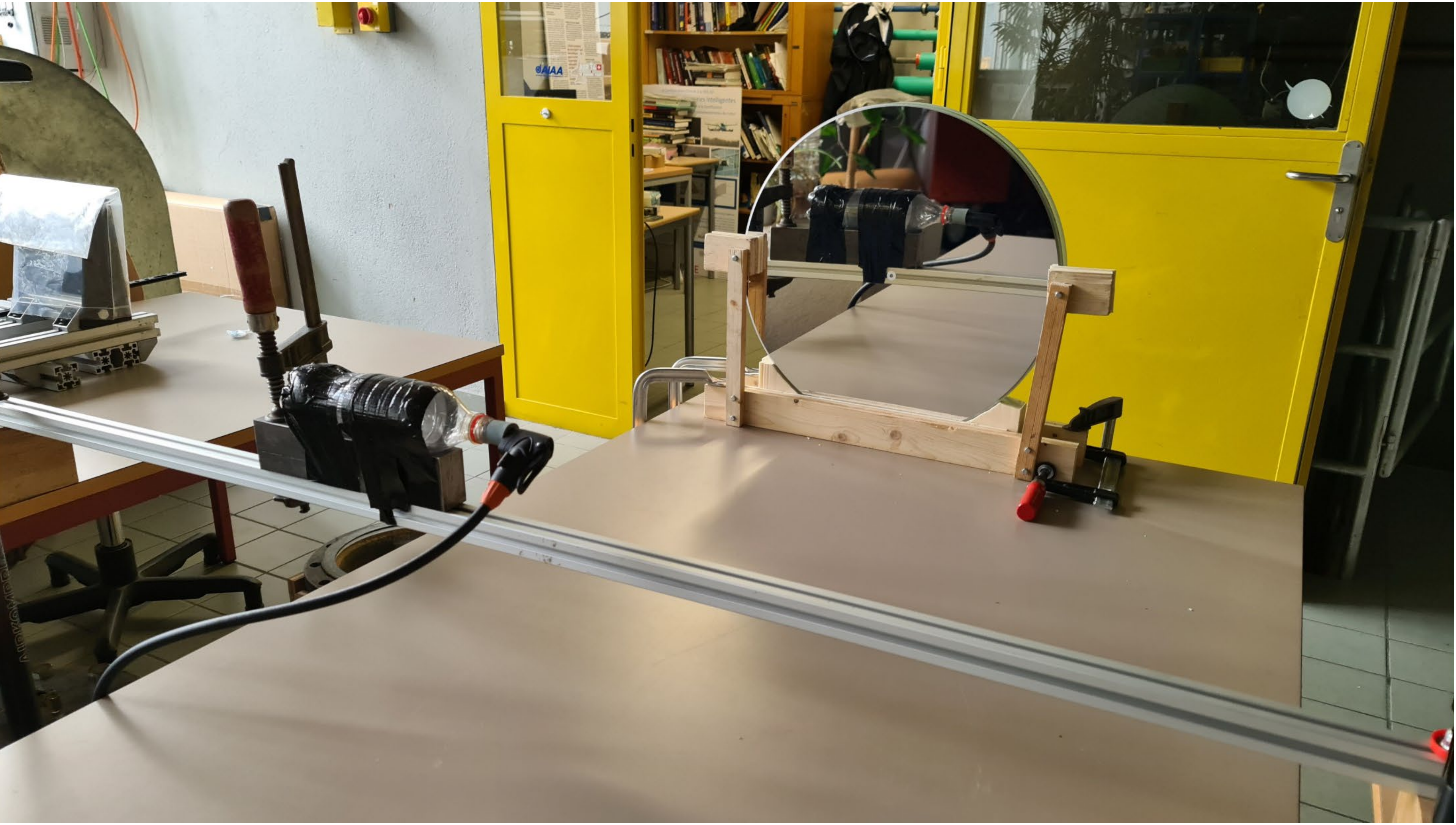


$$p_1 = p_{e/s} > p_{b/a}$$

sous-détendu

$$p_1 = p_{e/s} > p_{b/a}$$

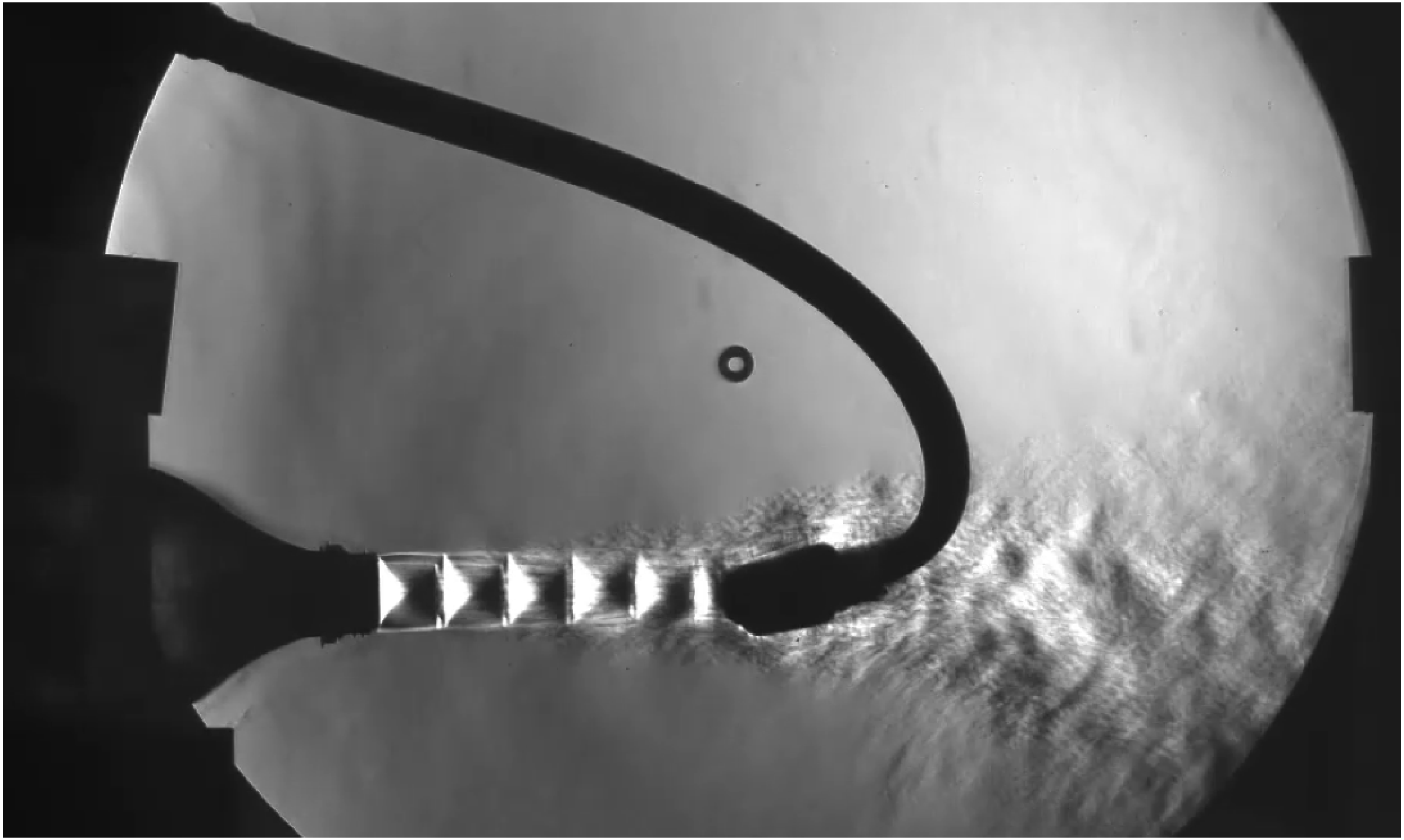
sous-détendu



$$p_1 = p_{e/s} > p_{b/a}$$

sous-détendu

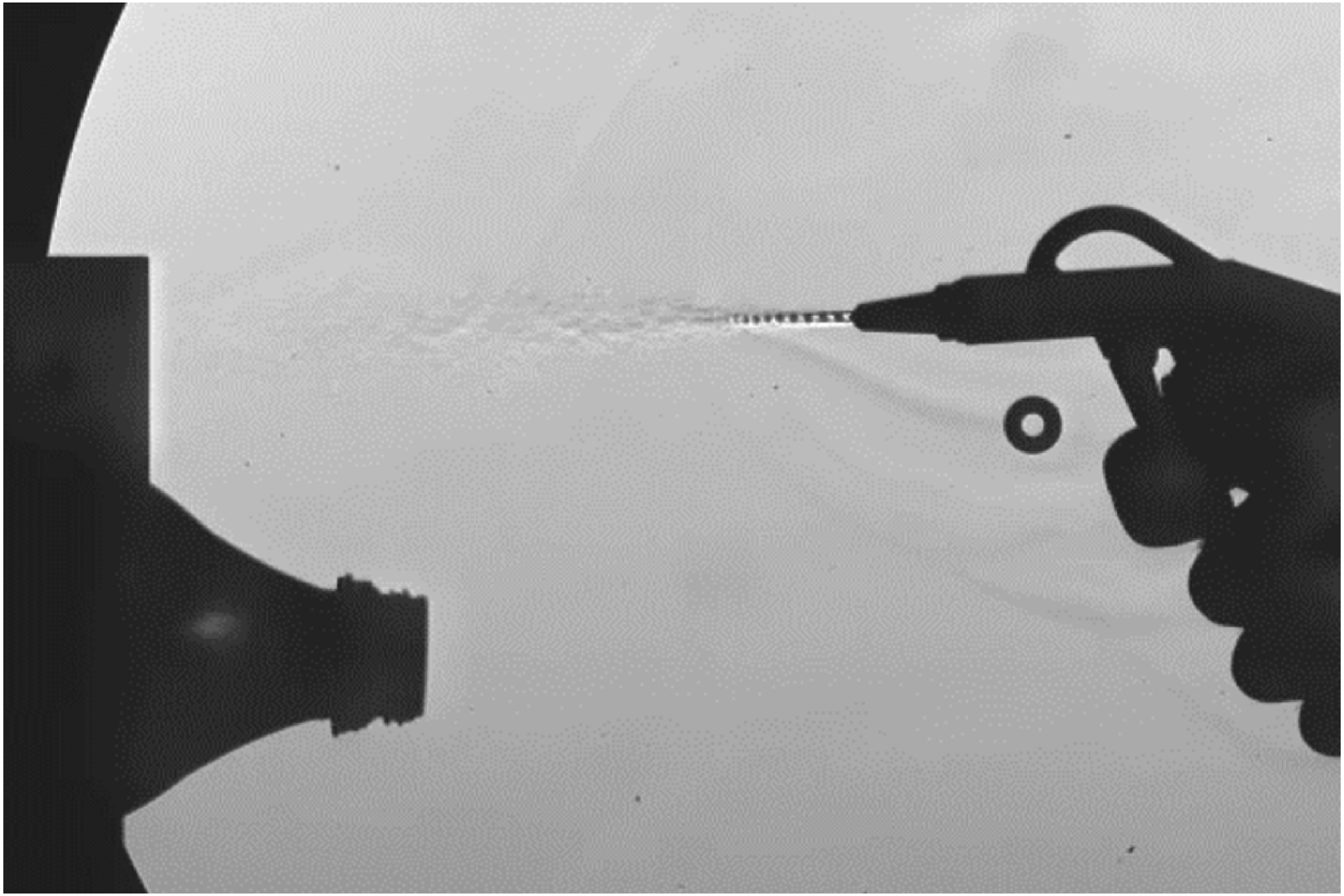
Jet de bouteille – sous-détendu



$$p_1 = p_{e/s} > p_{b/a}$$

sous-détendu

Air comprimé – sous-détendu

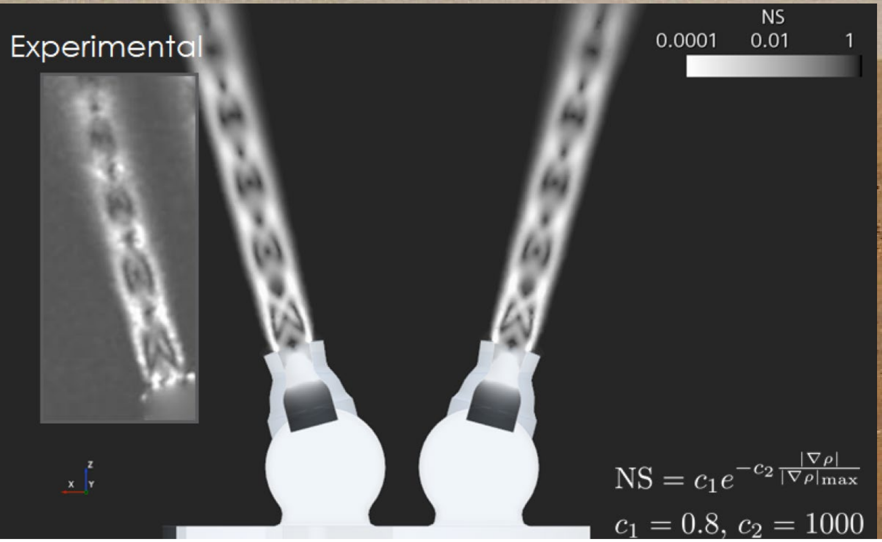


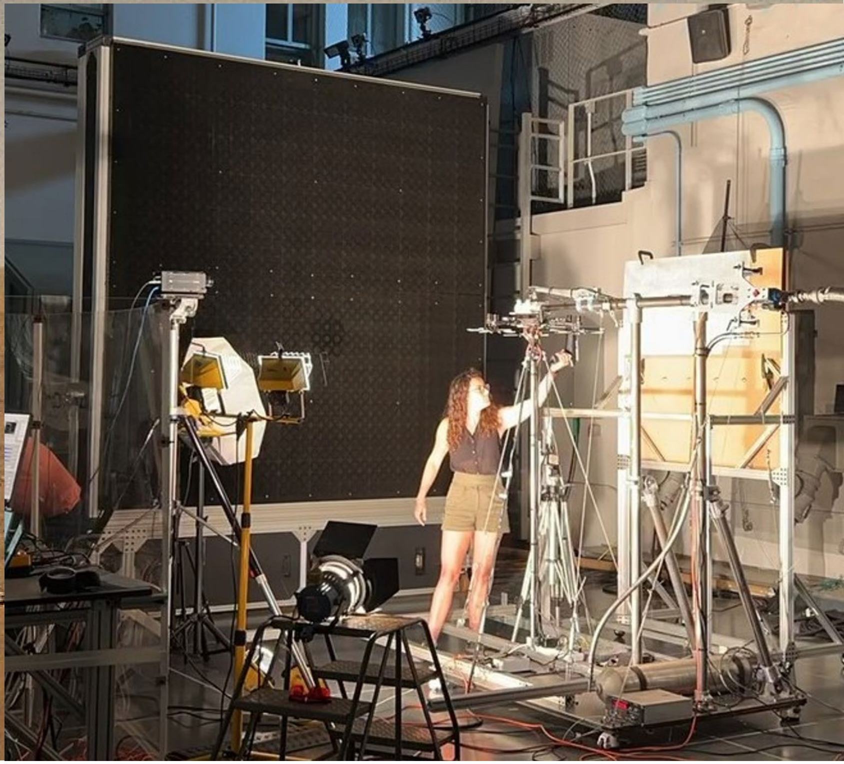
Mars helicopter

Jet Propulsion Laboratory
California Institute of Technology

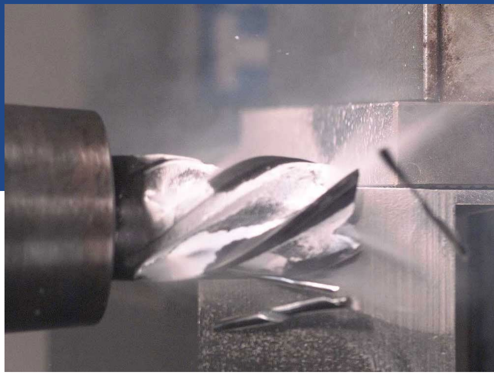
$p_1 = p_{e/s} > p_{b/a}$

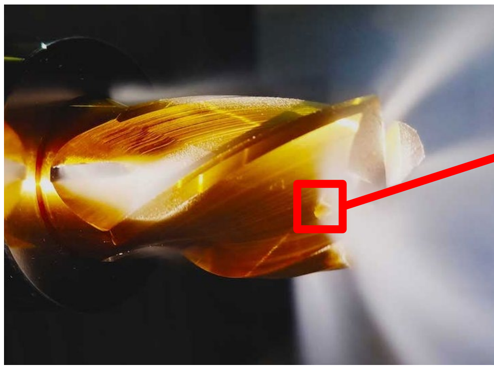
sous-détendu





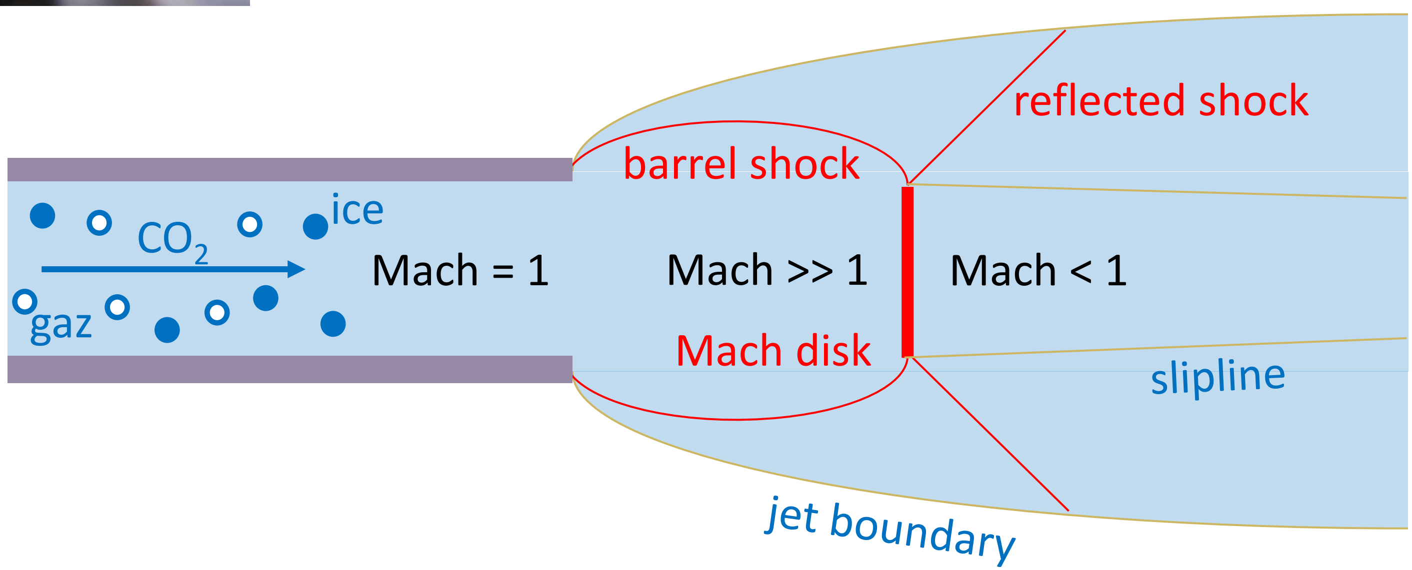
Ecoulement **hautement sous**-détendu (**highly underexpanded**)





$$p_1 = p_{e/s} \gg p_{b/a}$$

hautement sous-détendu



Ecoulement hautement sous-détendu (highly underexpanded)

$$p_1 = p_{e/s} \gg p_{b/a}$$

hautement sous-détendu