



Aeroacoustic Research and Noise Reduction for Aircraft Mechanisms, Technologies, Perspectives

Prof. Jan DELFS – DLR (Germany)



9 - 11 April 2025, Antibes Juan-les-Pins (France)



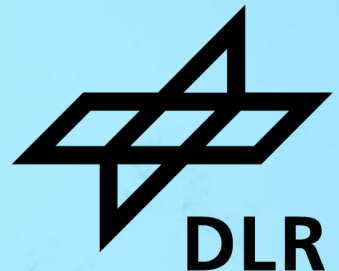
AEROACOUSTIC RESEARCH AND NOISE REDUCTION FOR AIRCRAFT – MECHANISMS, TECHNOLOGIES, PERSPECTIVES –

FAN 2025 09-11 April 2025, Antibes, France

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Braunschweig, Germany



Outline

- noise reduction – why?
- aerodynamic sources of sound at transport aircraft (...and fans)
- noise reduction technologies – from basics to fly-over tests and back
- source noise localization & quantification – prerequisite for low noise design
- summary + conclusions



Why? Community noise !

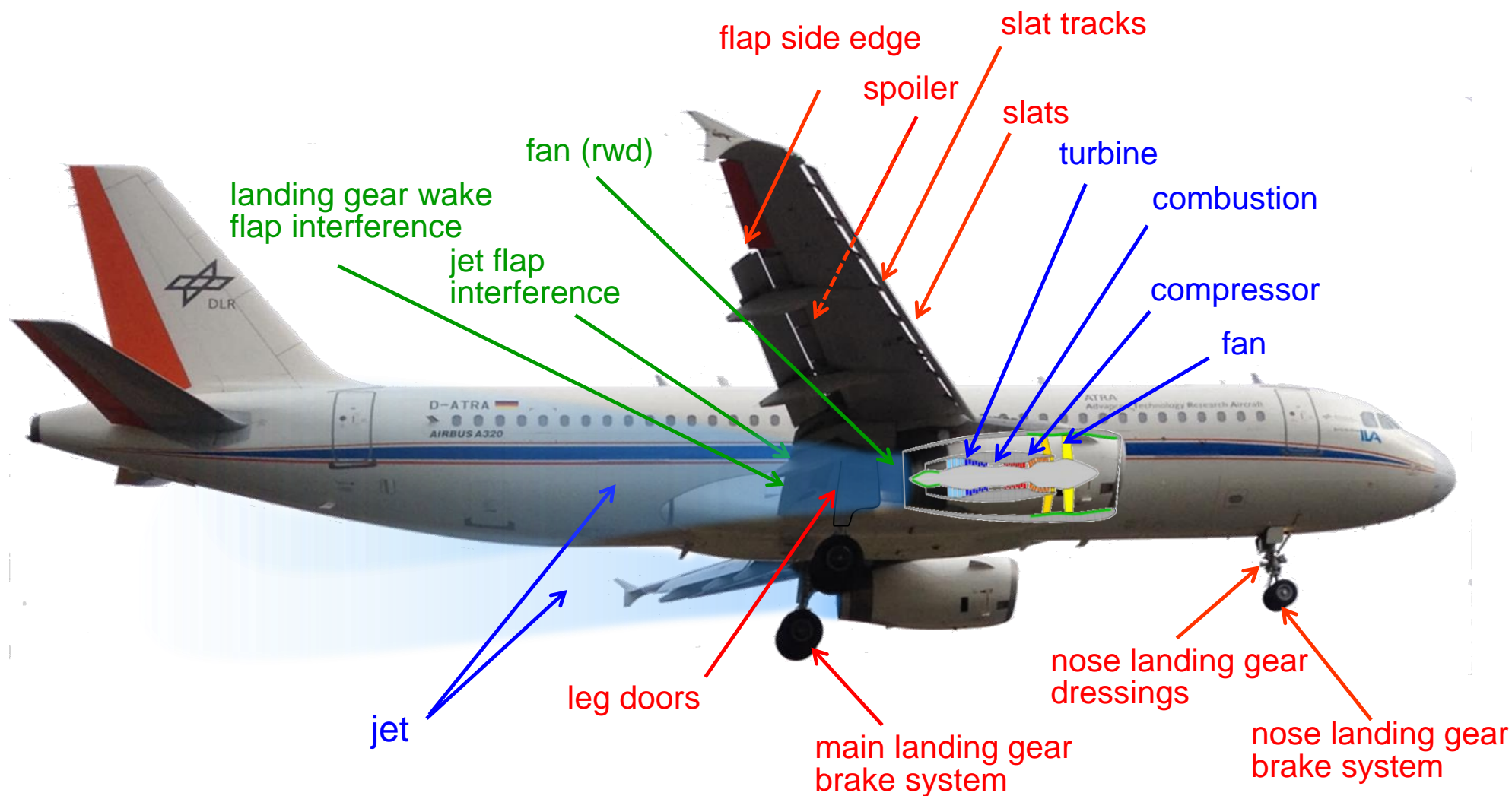
- source noise reduction
- flight paths/routing
- passive measures (sound insulation buildings)
- air traffic restrictions



- By 2050 technologies, operational improvements and noise abatement procedures reduce the perceived noise emission of flying aircraft by 65%¹³ per operation relative to the 2000 baseline;

¹³ a reduction of 65% equals ~ **-15dB**/operation = **-97%** in sound intensity

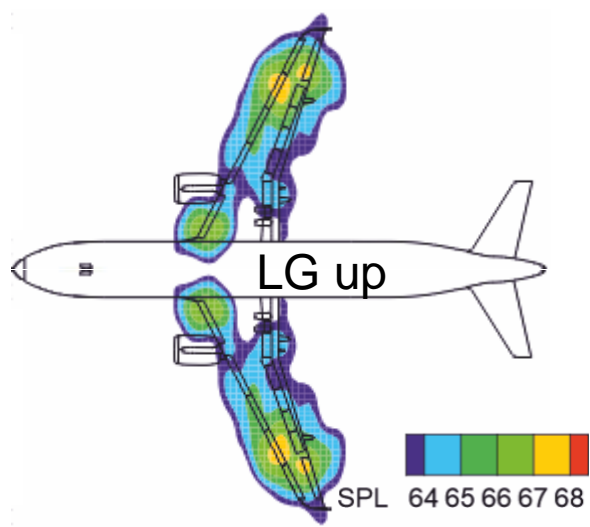
Sources of sound at turbofan aircraft



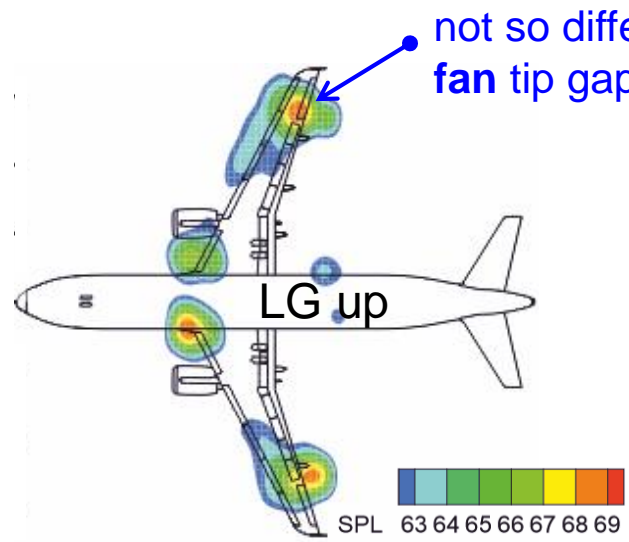
sources:

engine
airframe
installation

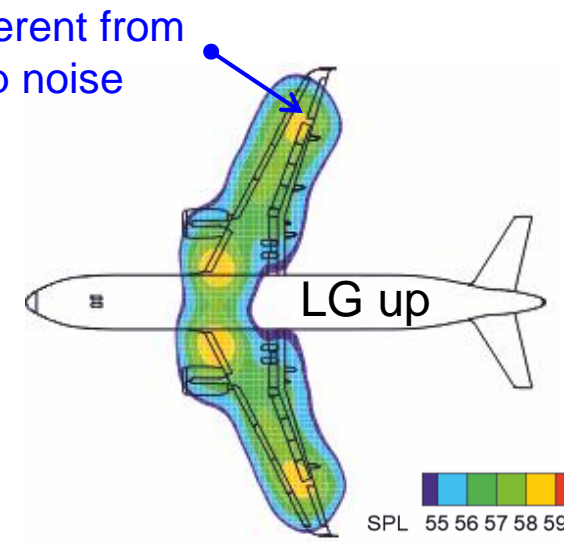
Sources of airframe noise – flyover array results



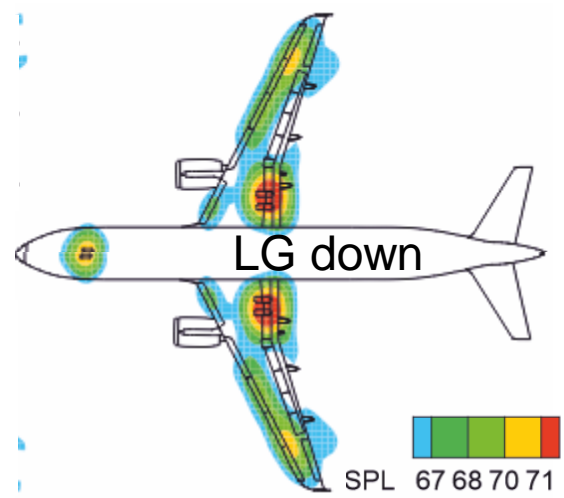
$f_m = 800\text{Hz}$



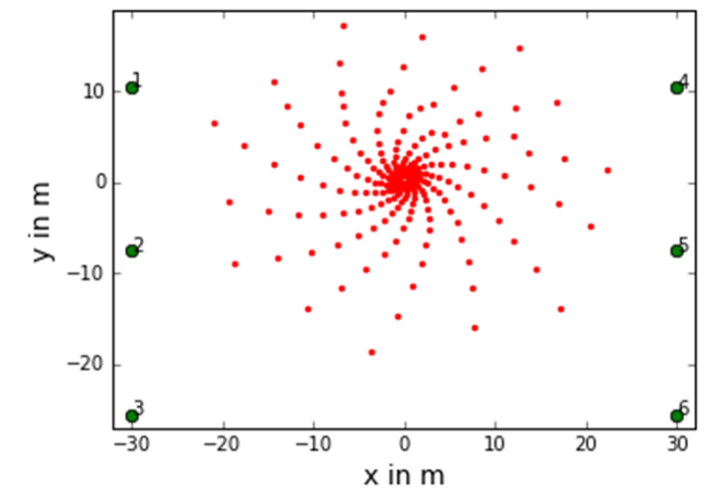
$f_m = 1250\text{Hz}$



$f_m = 3150\text{Hz}$



flaps full – 170kts overhead



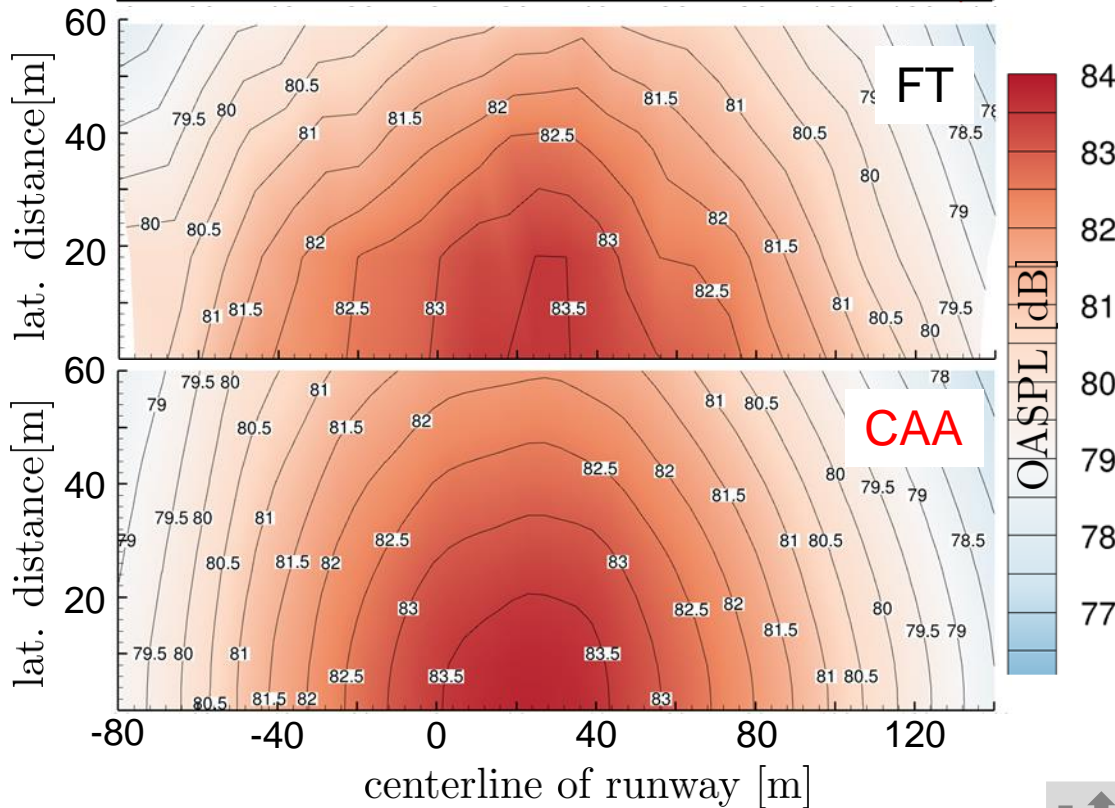
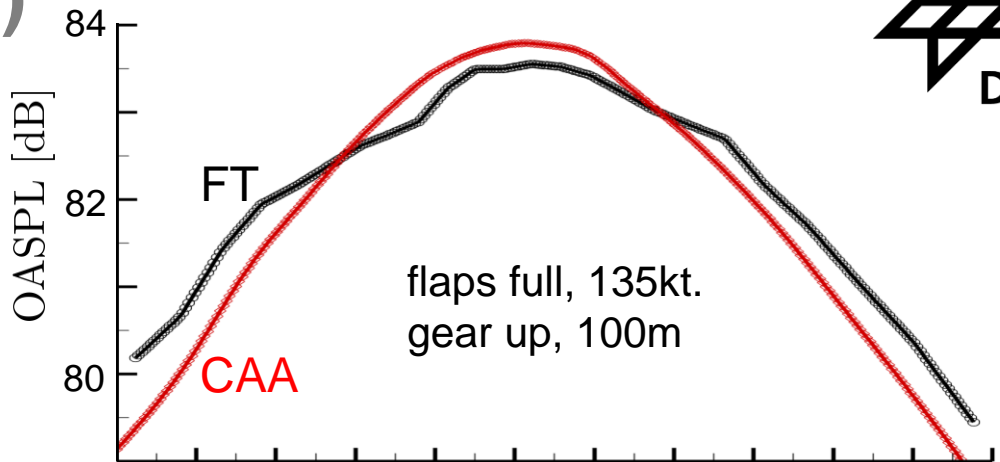
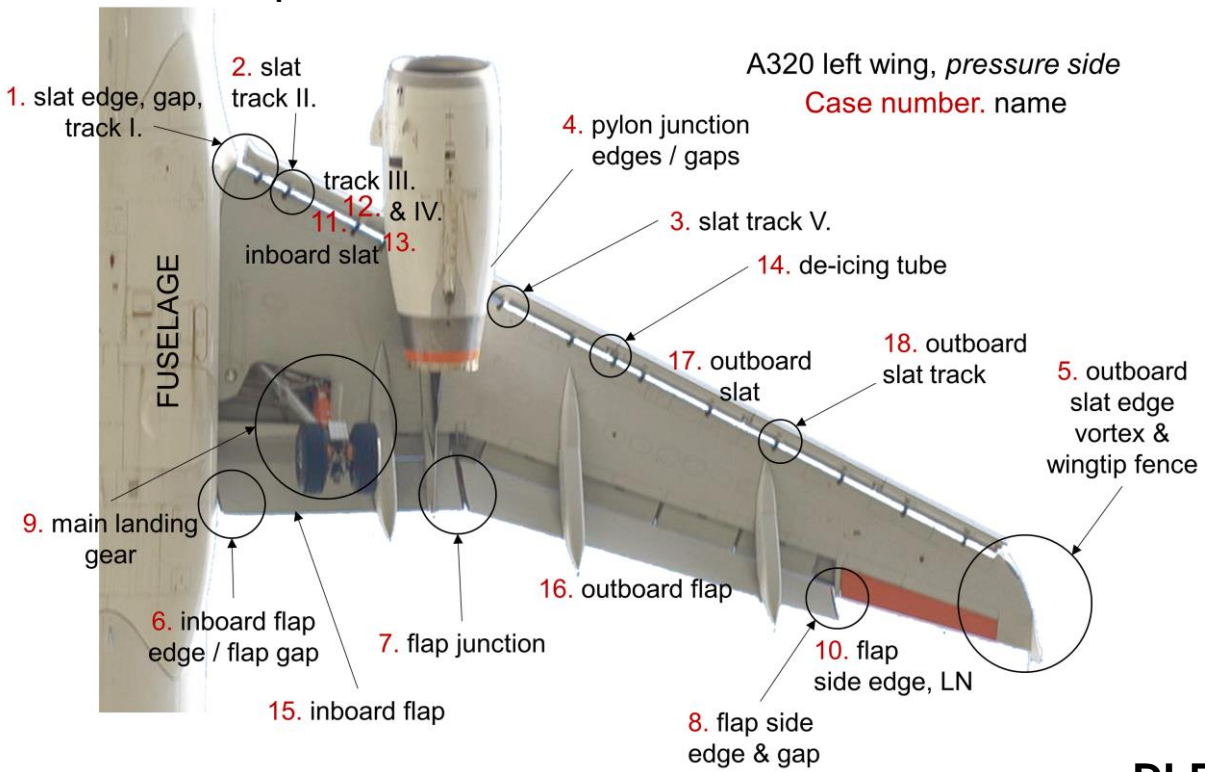
Full scale Flyover simulation (ATRA)



mean flow: **TAU**
 sources: **FRPM**
 acoustics: **DISCO++/FW-H**



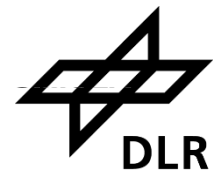
component wise simulation



DLR SIAM



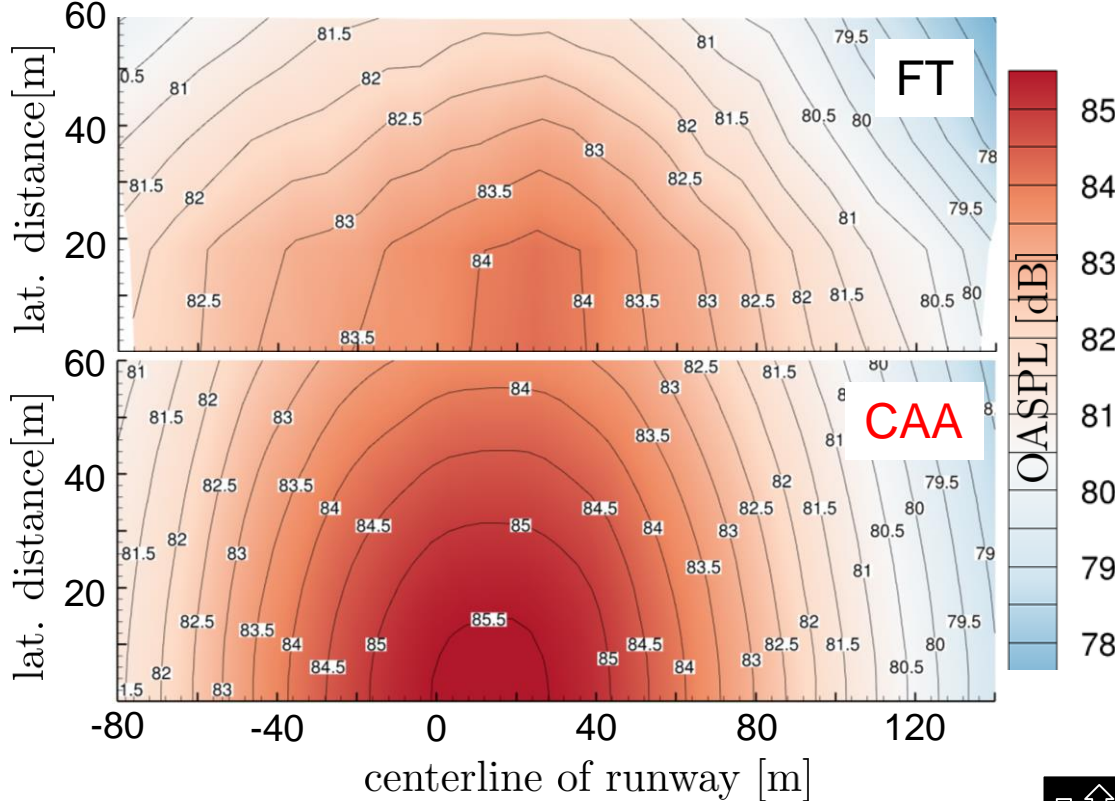
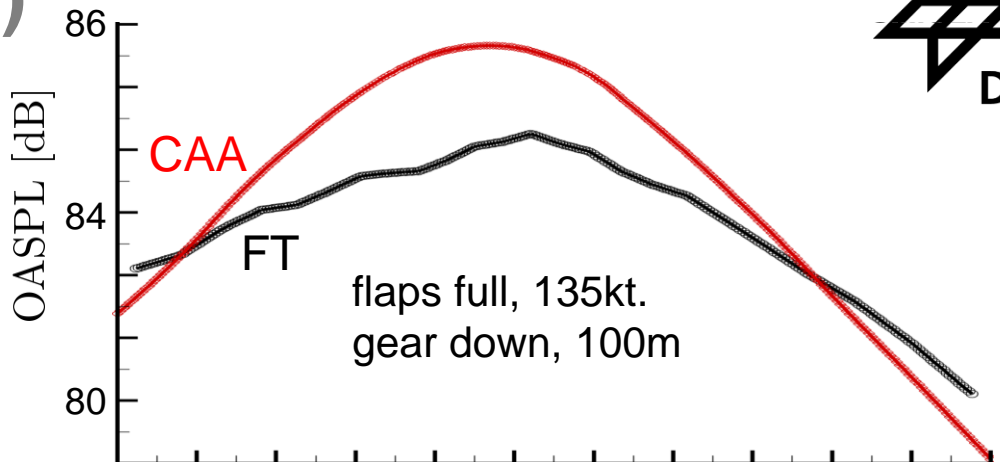
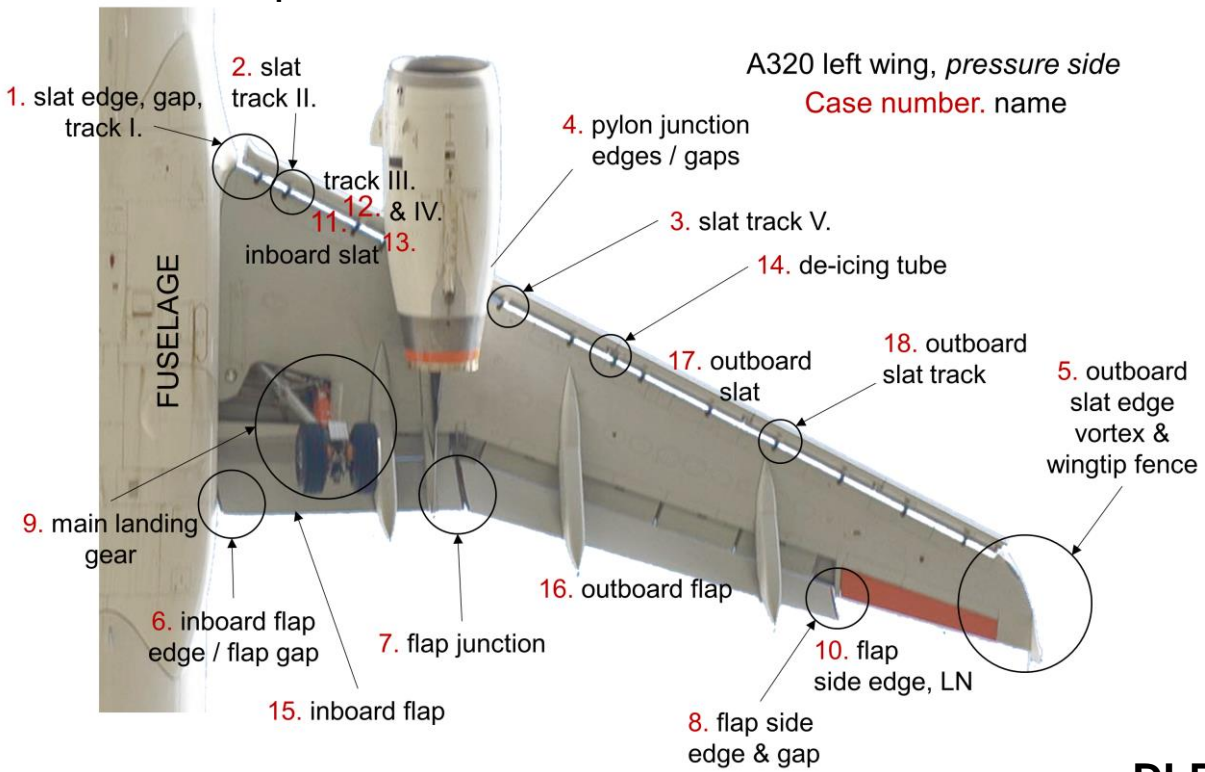
Full scale Flyover simulation (ATRA)



mean flow: **TAU**
 sources: **FRPM**
 acoustics: **DISCO++/FW-H**



component wise simulation





LN-ATRA

- A DLR project to **demonstrate** the potential of **noise reduction technologies (NRT)** for current transport aircraft
- Implementation/test of known airframe+jet NRTs on real a/c

Flight test for noise reduction technologies



Concept:

Test of all measures simultaneously at DLR Advanced Technology Research Aircraft

Programme:

- Reference test 2016
- 1. part test 2017 (co-operation with EU AFLoNext)
- 2. part test 2018 (5 years preparation)
- main test, 1. part 2019
- ~~main test, 2. part 202x~~ – prepared, not flown –

Partners:

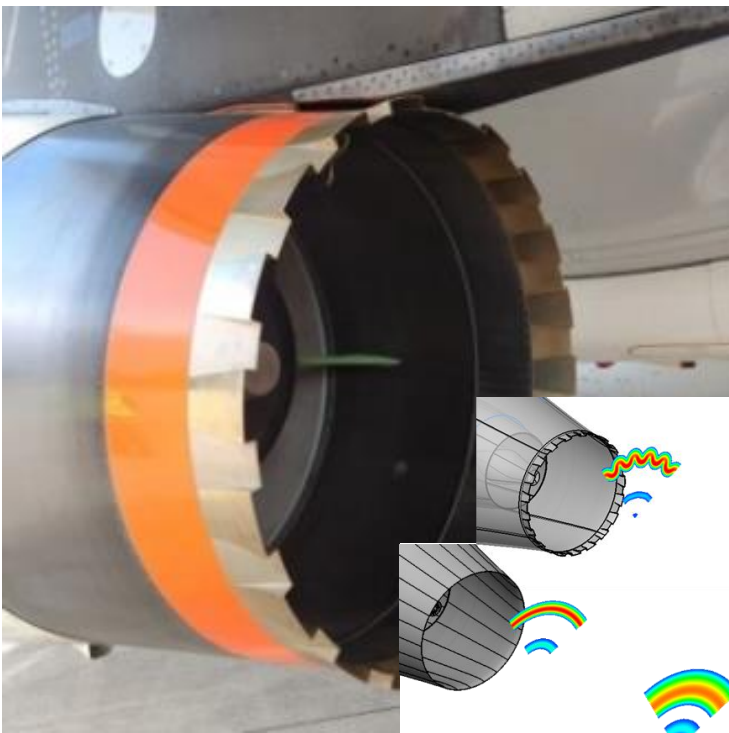


photo: M. Lindner 2018

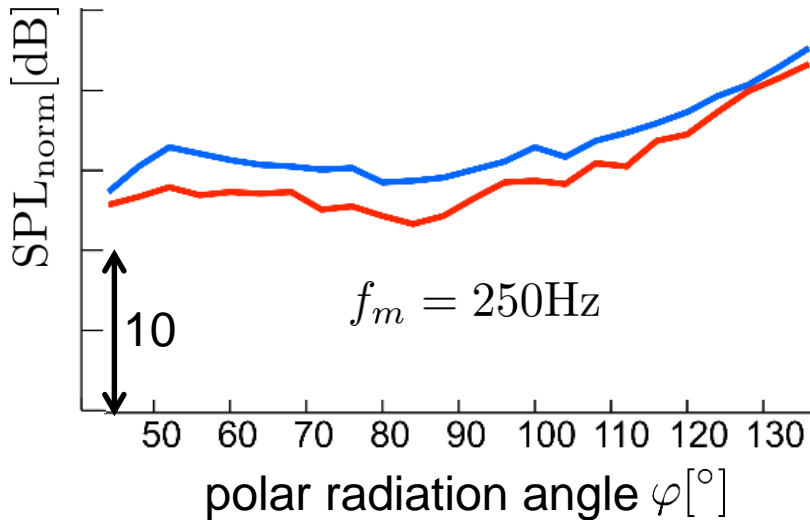
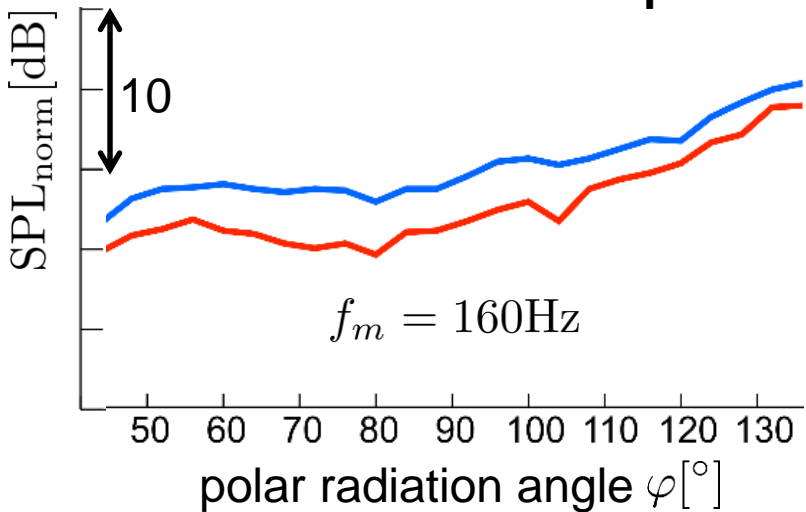
Jet noise reduction



Nozzle modification



take-off – flaps 2: 22°/20° - gear up



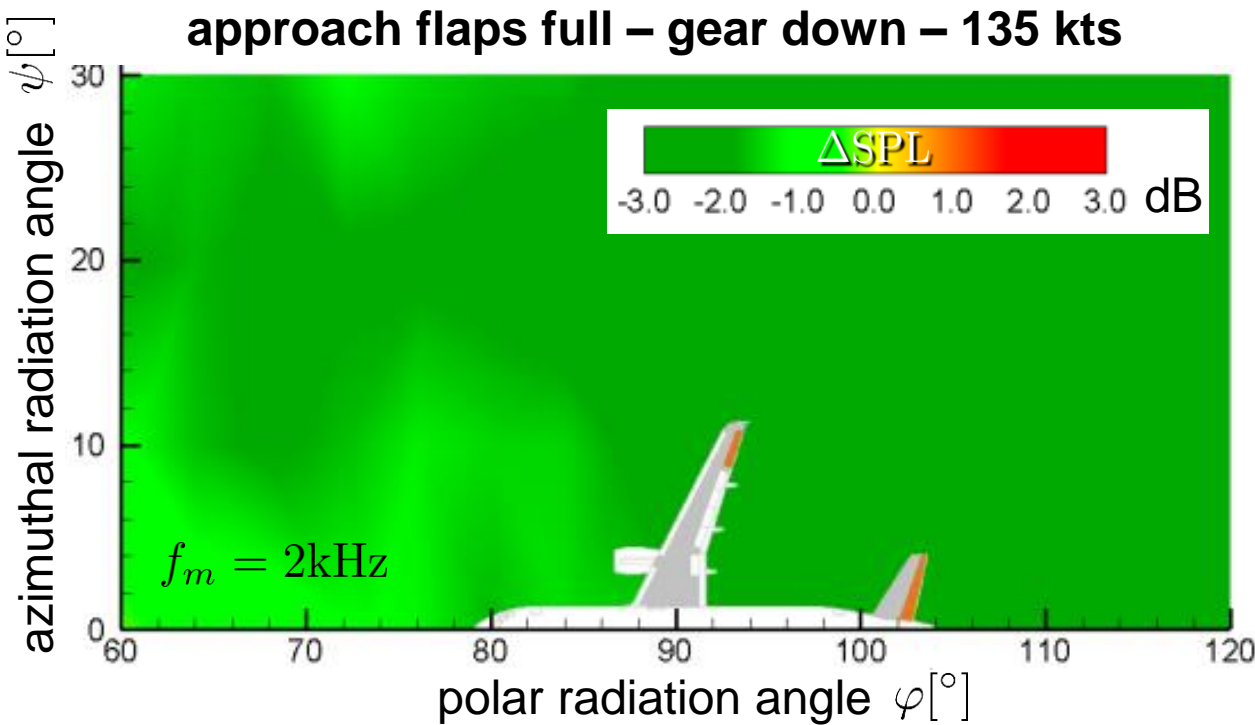
$$SPL_{\text{norm}} = SPL_{\text{meas}} - 80 \lg \left(\frac{v_{\text{jet}} - v_{\text{tas}}}{c_{\text{ref}}} \right) [\text{dB}]$$

- significant reduction at low frequencies, slight increase (~1dB) at high frequencies

Landing gear noise reduction



Nose/Main LG modification

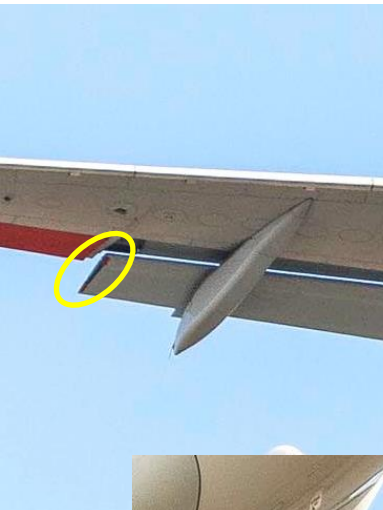


- wide area broadband noise reduction ~ 2-3dB (single mics!)

High Lift noise reduction



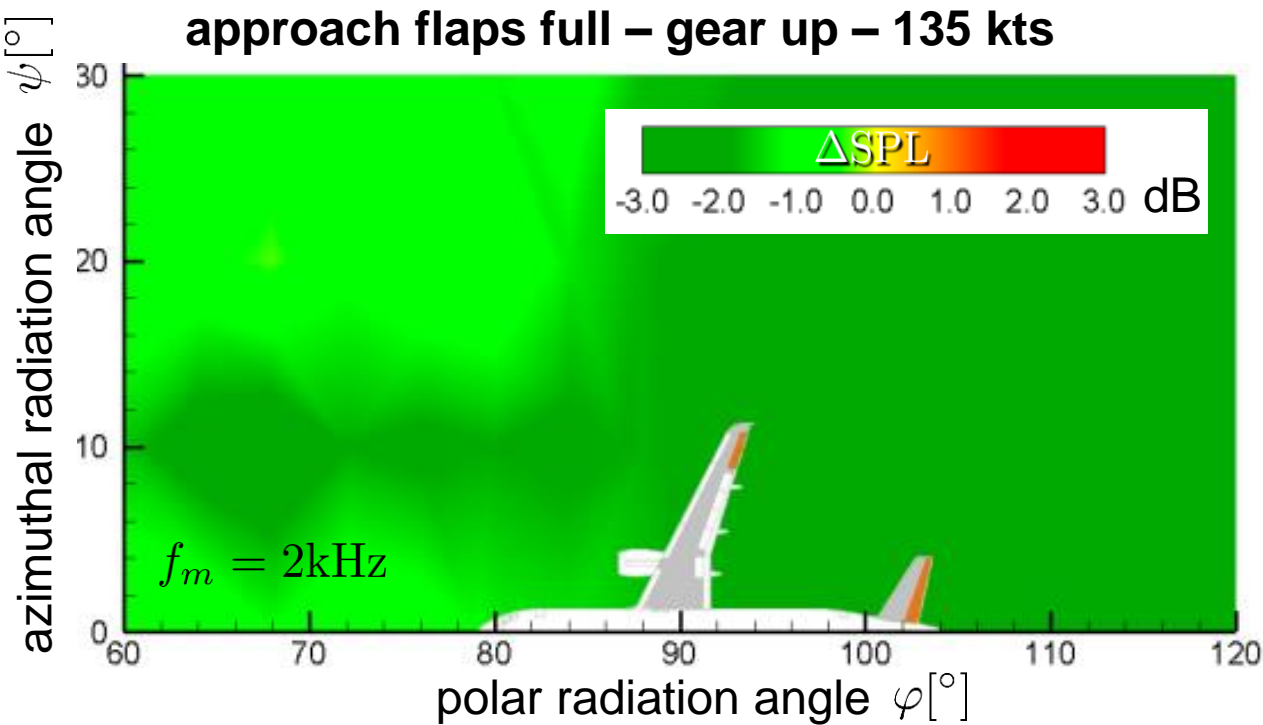
HLD side edge modification



aluminum foam



open cell urethane foam

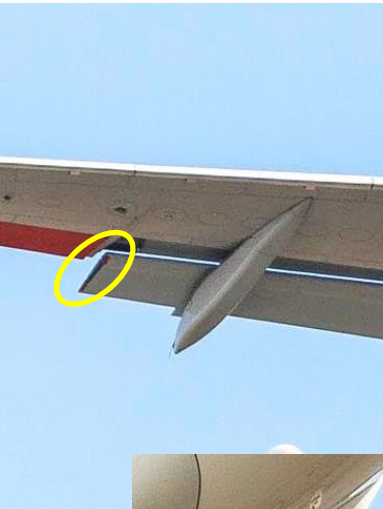


- wide area broadband noise reduction ~ 2-3dB (single mics!)

High Lift noise reduction



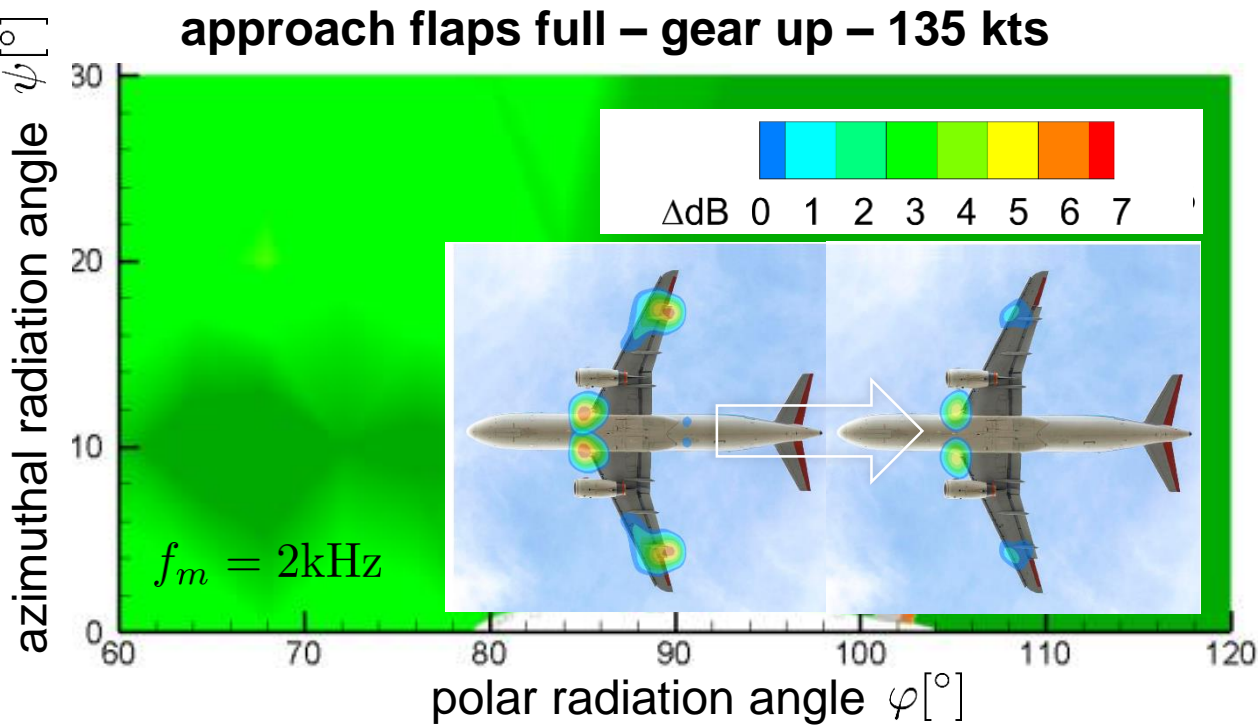
HLD side edge modification



aluminum foam

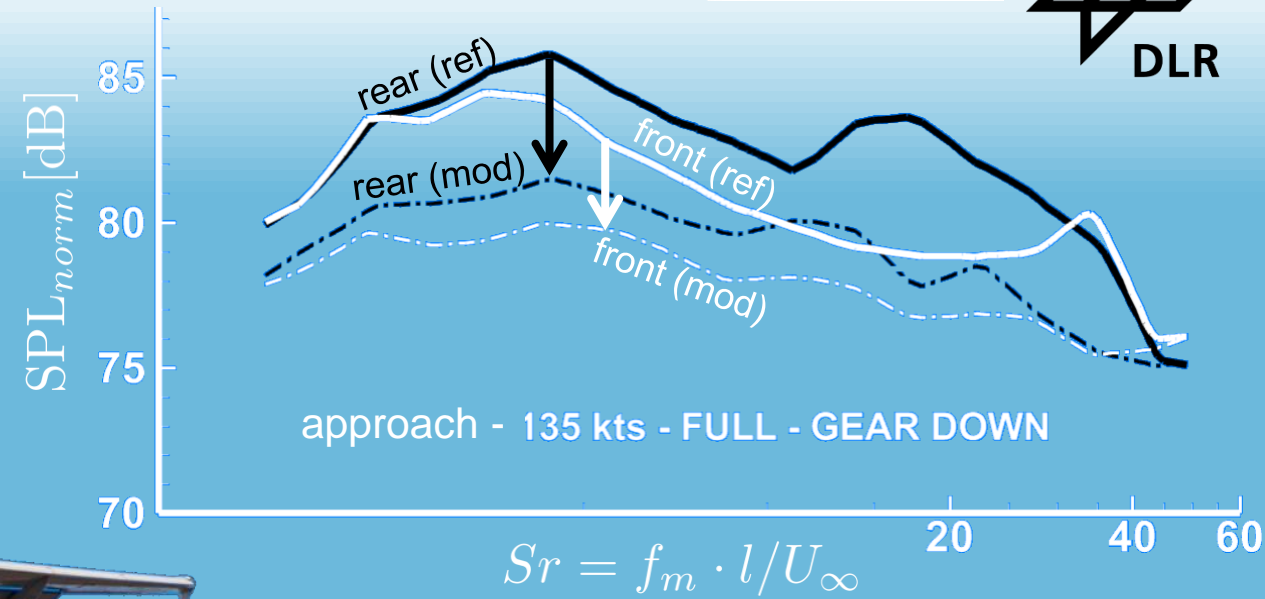
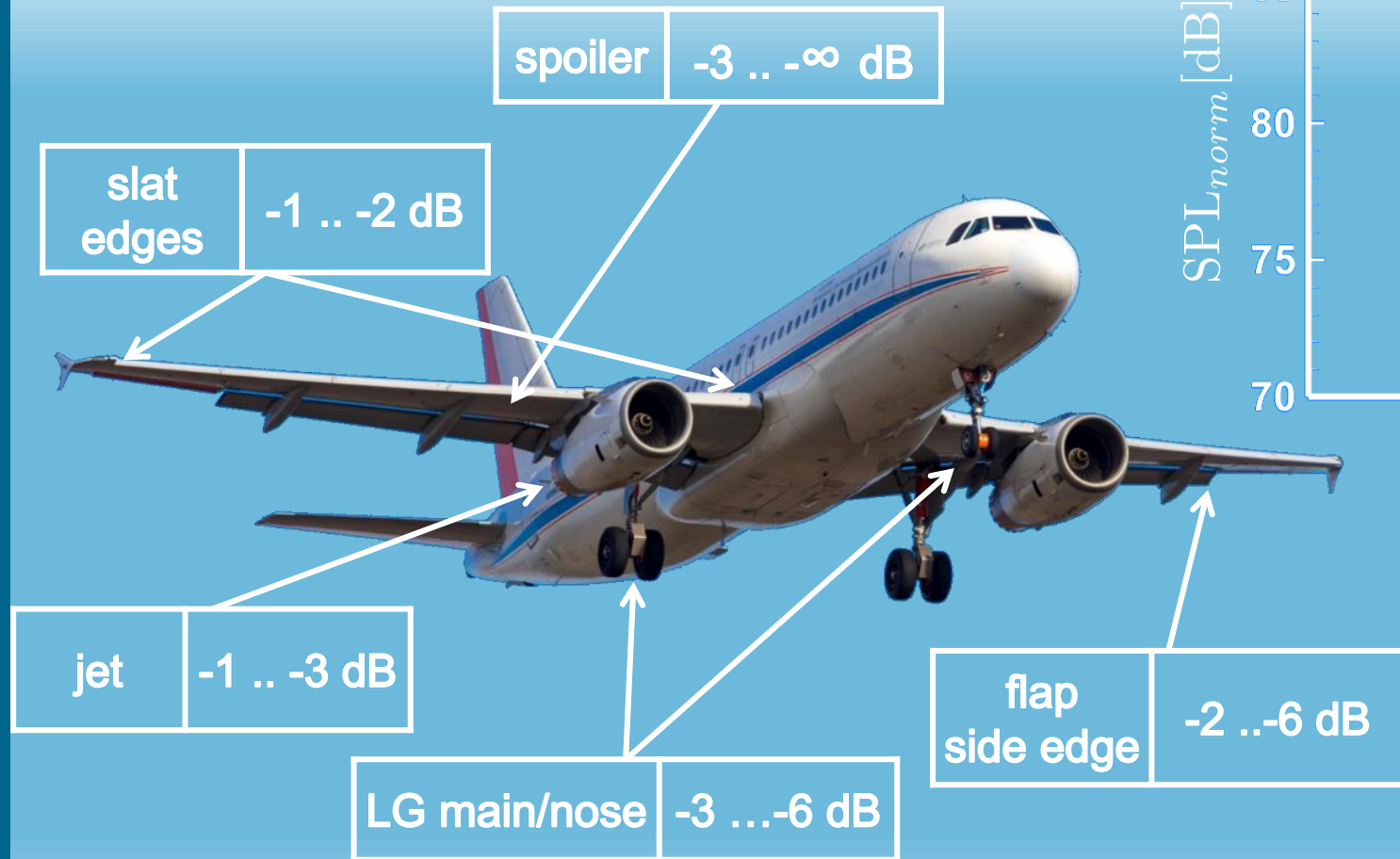


open cell urethane foam



- wide area broadband noise reduction ~ 2-3dB (single mics!)

Low noise ATRA - synopsis



- ✓ broadband reduction 3 – 4 dB for standard approaches
- ✓ spoiler noise eliminated
- ✓ 1 – 2 dB reduction at departure

- up to **5dB reduction** at approach (if including slat modification)

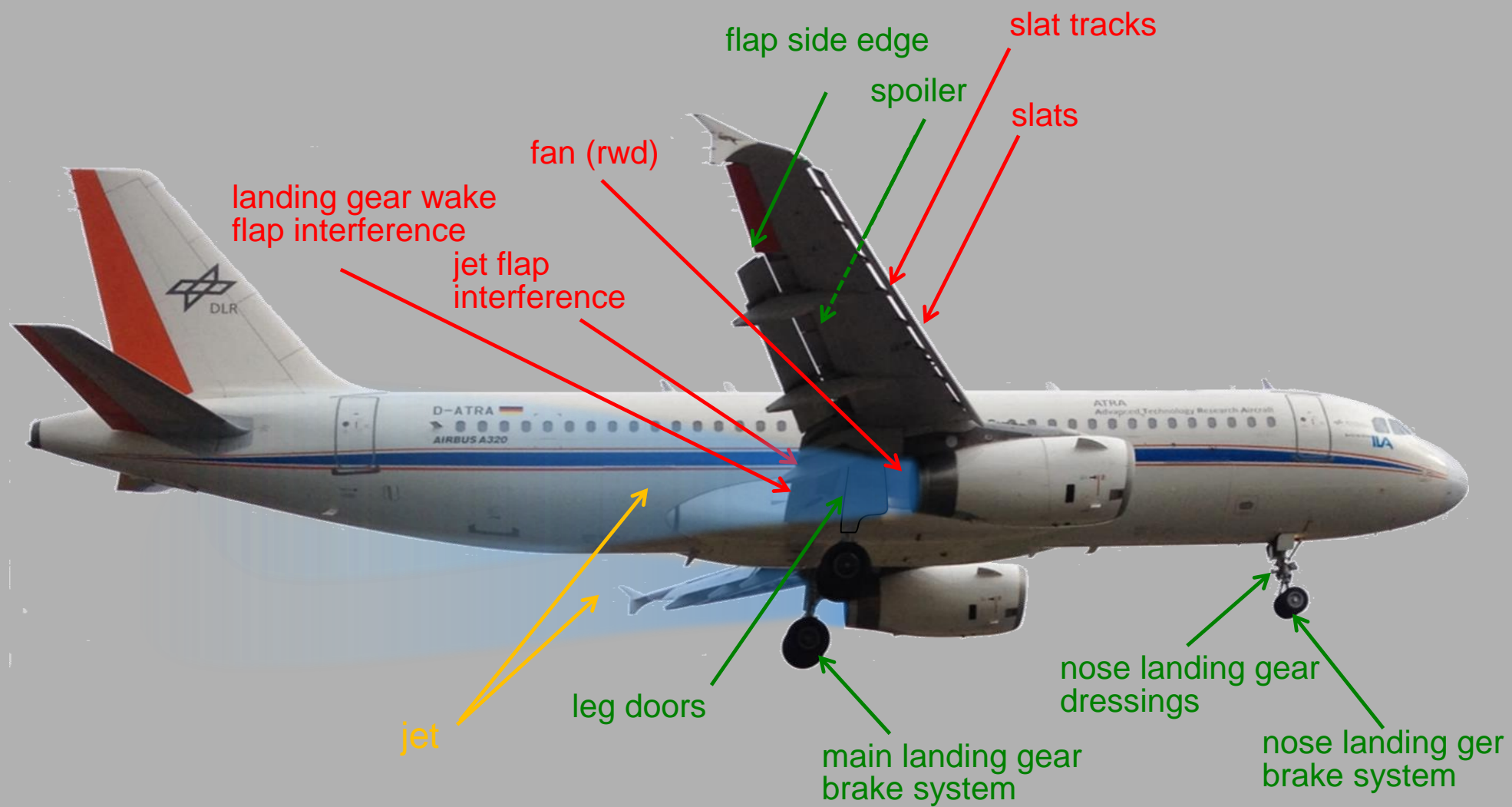
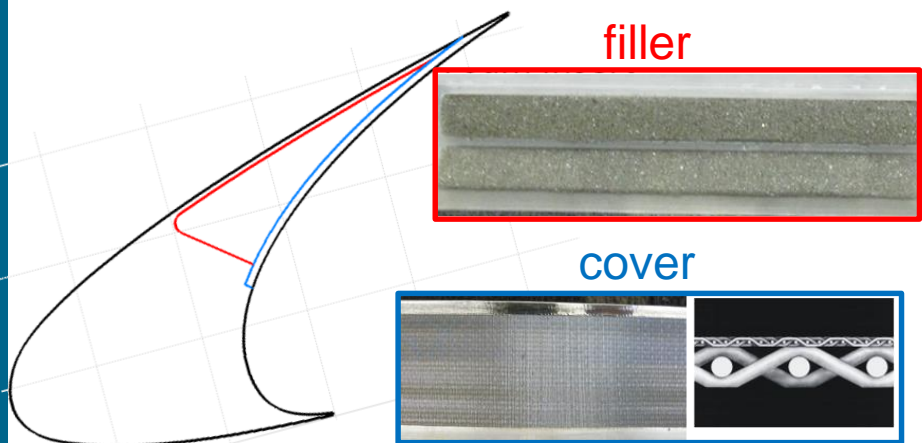


Photo: H. Siller

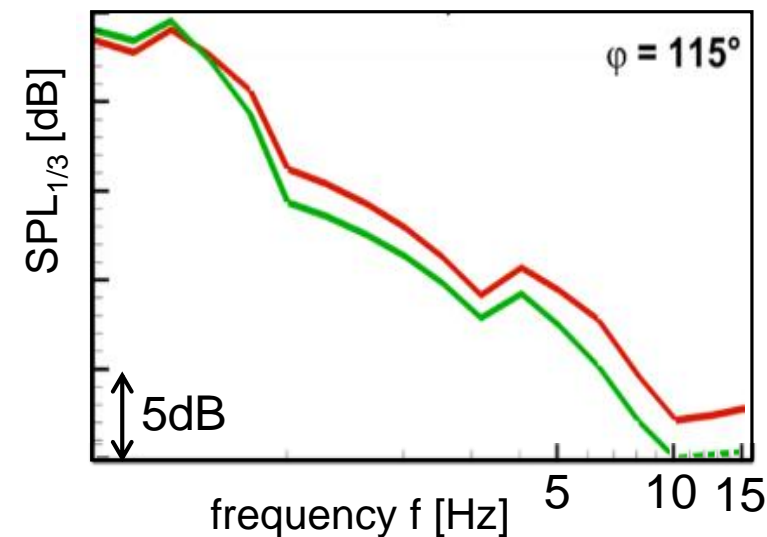
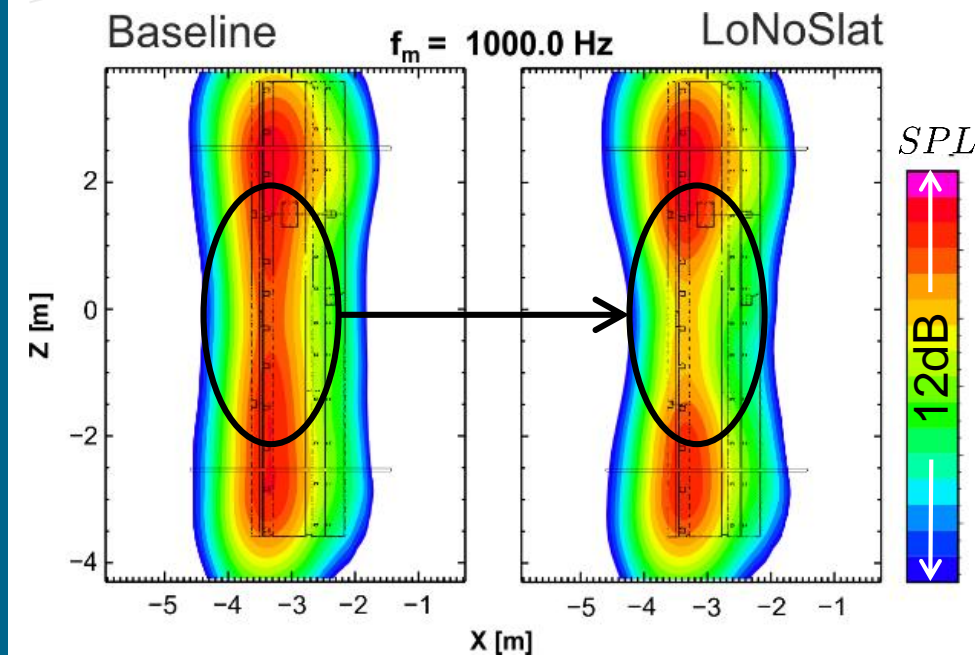
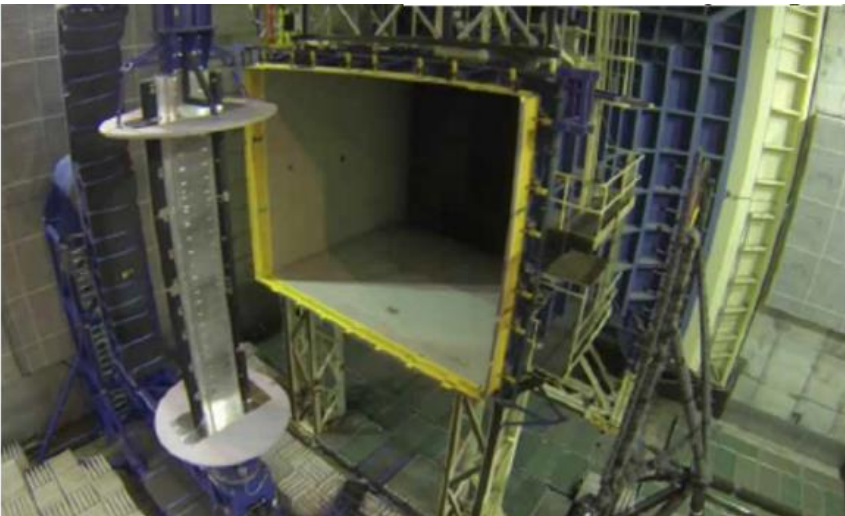
BEYOND LNATRA

→ Further research on sources of sound and respective noise reduction technology

SLAT - noise reduction by slat cove liner



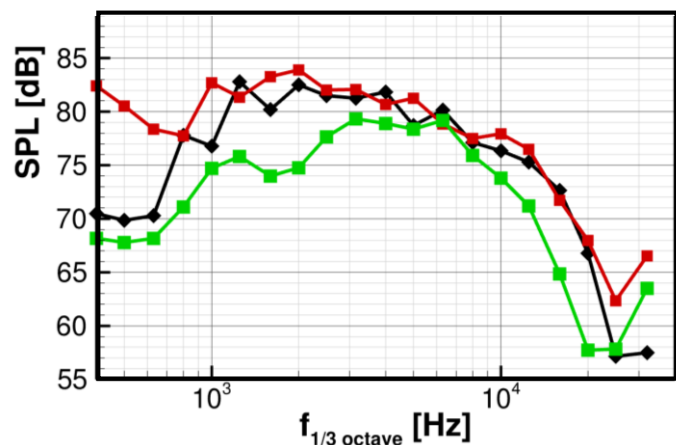
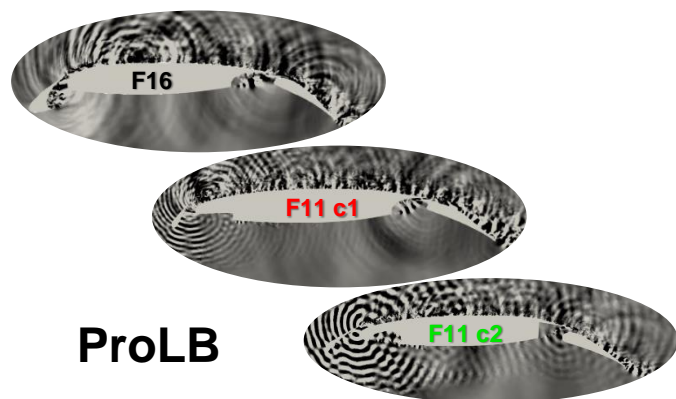
F15LS (4:1 sister of F16)
 1200 mm chord,
 Re ~ 4 Mio. @ 55 m/s



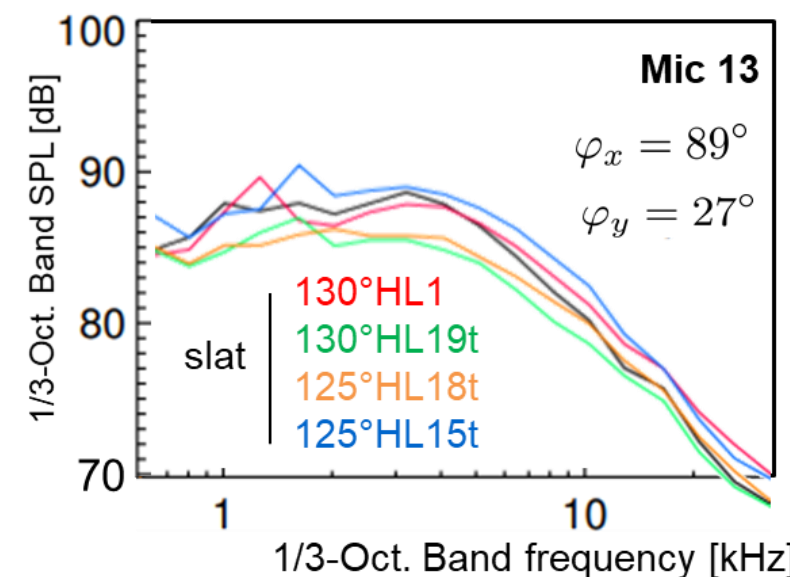
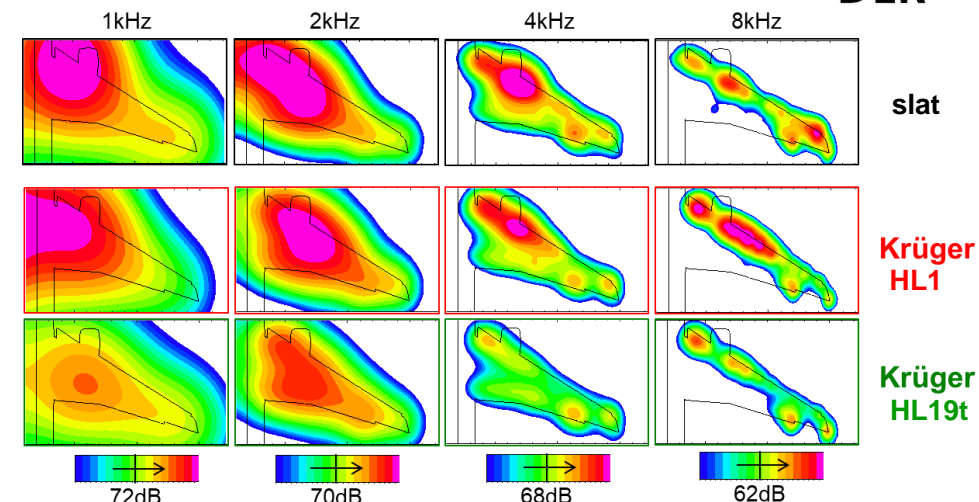
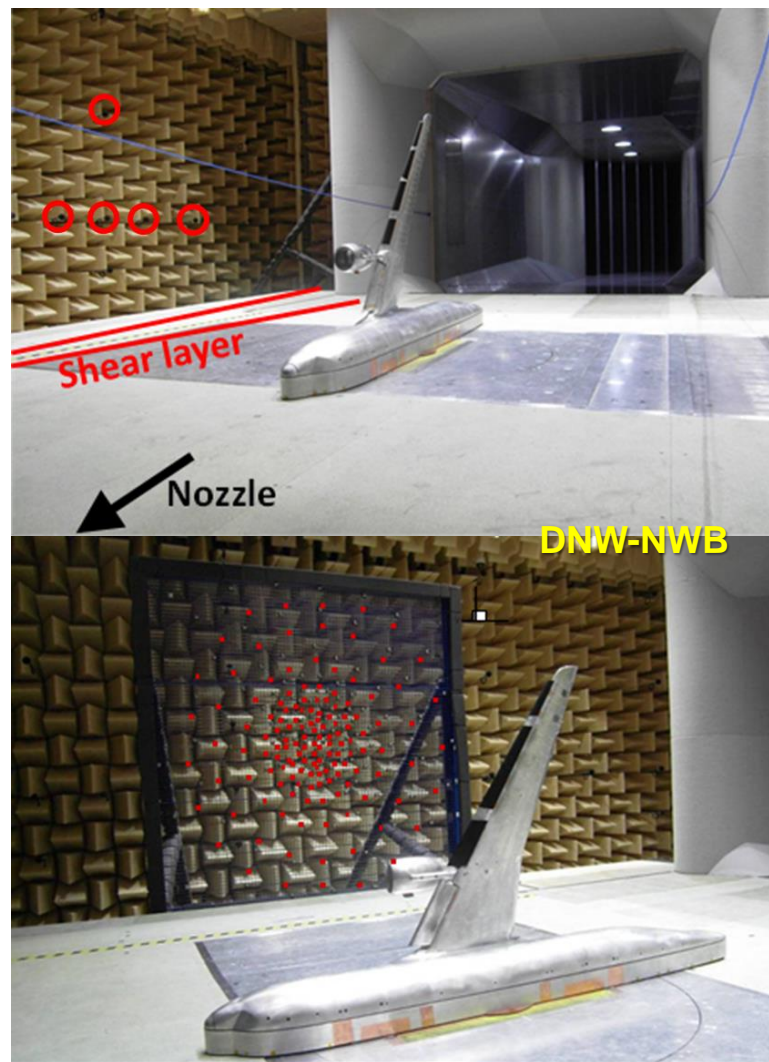
- 2-3 dB reduction broadband
- no lift penalty

Lufo MOVE.ON

Low noise high lift: leading edge device shapes

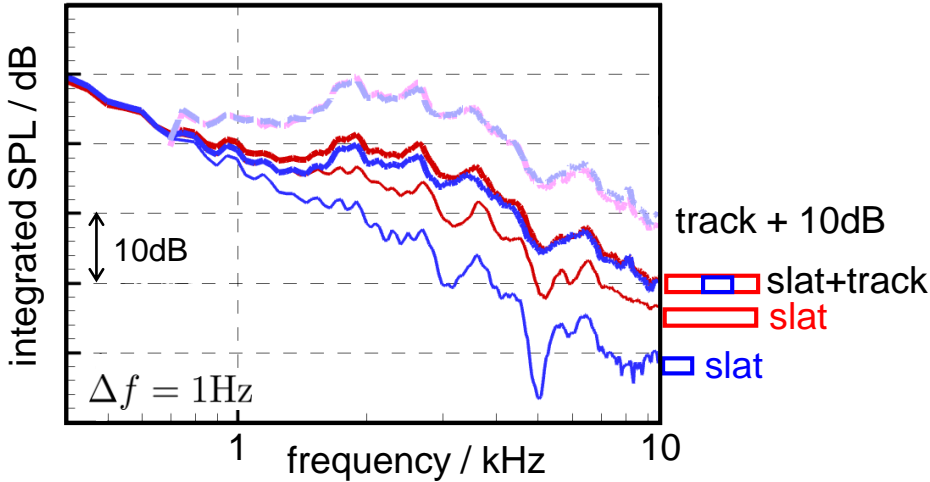
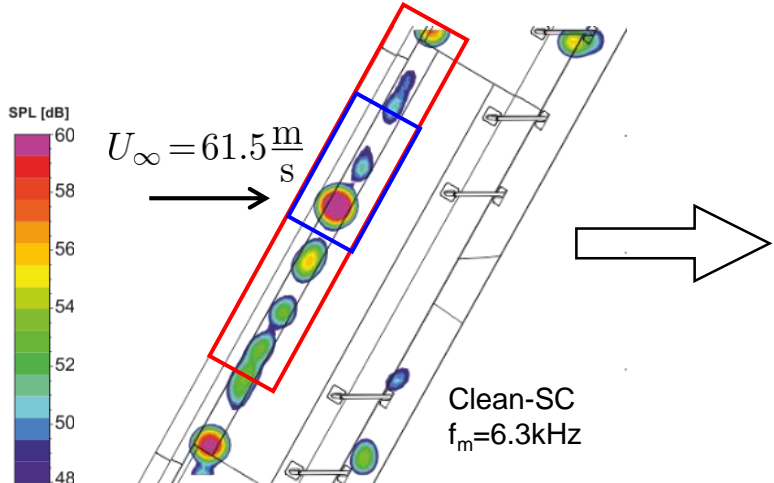
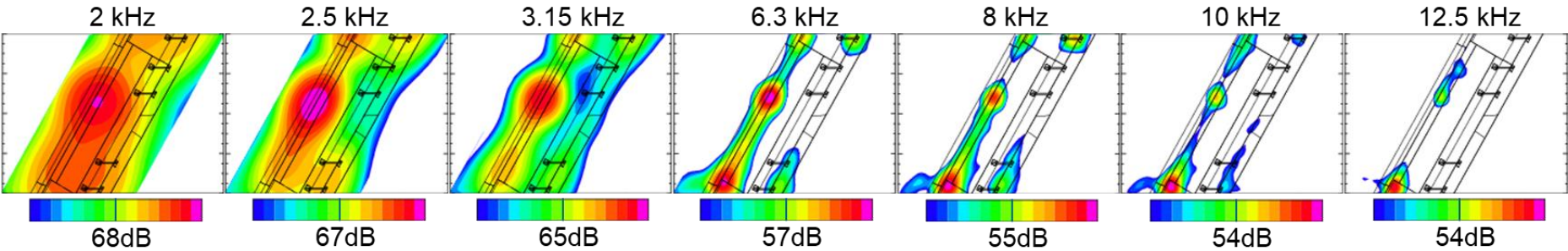


same high lift performance



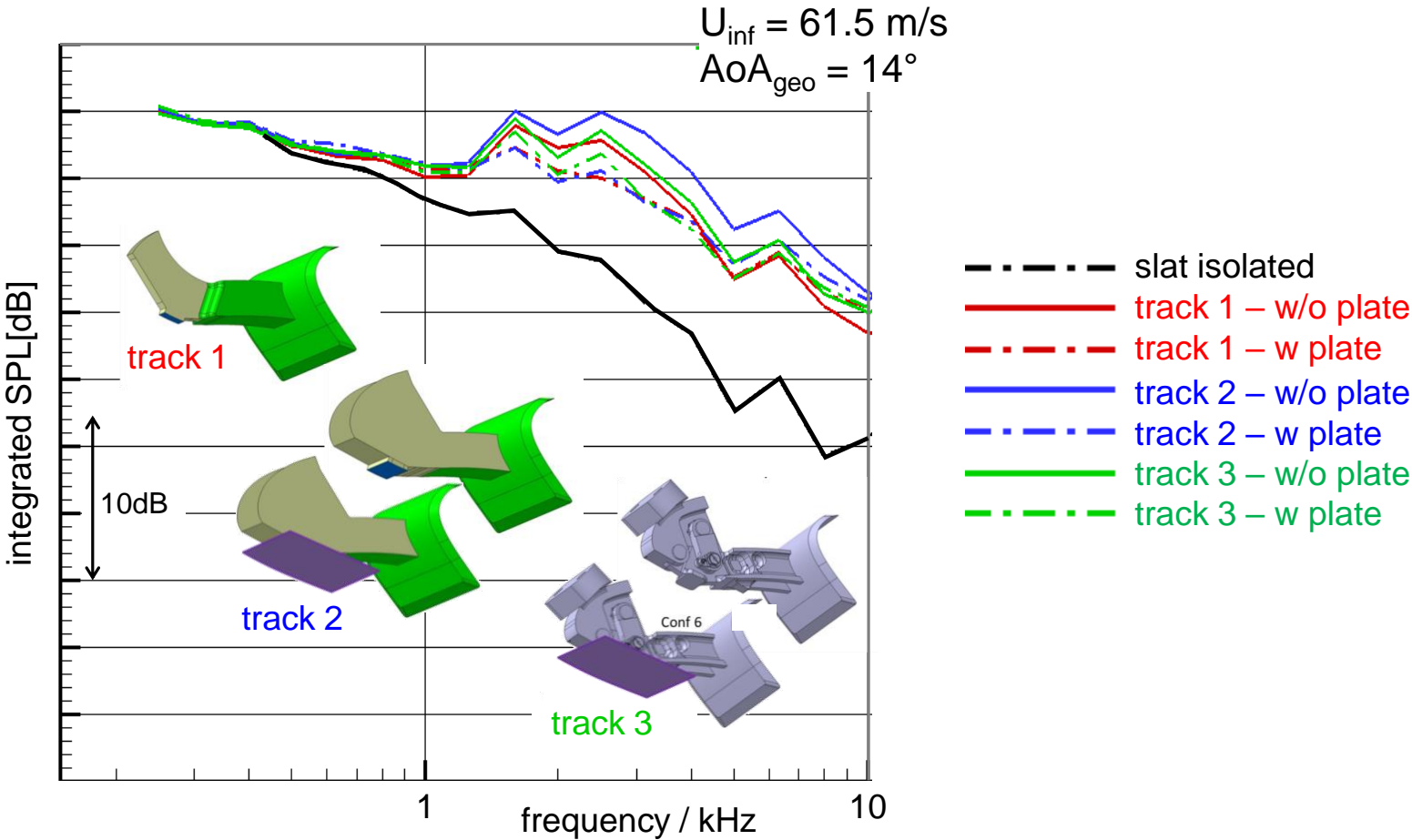
→ 3D proof of low noise potential of Krüger flaps

Importance of SLAT TRACK noise



- track noise may dominate spectrum in wide frequency range

Importance of SLAT TRACK noise – influence of shape

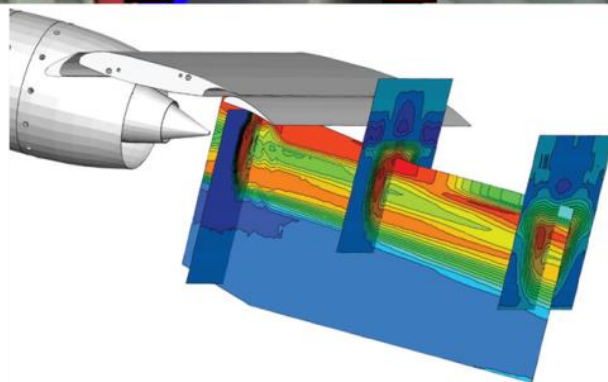
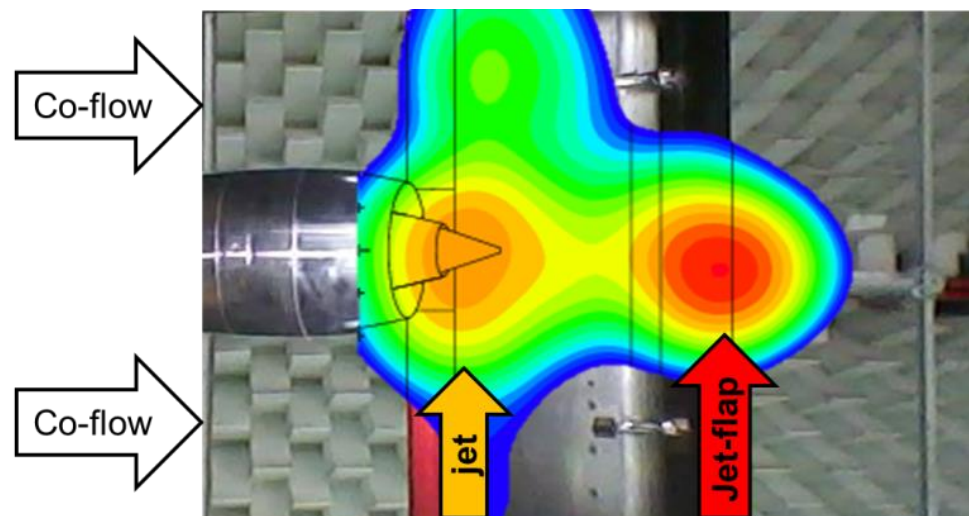


- noise reduction by design

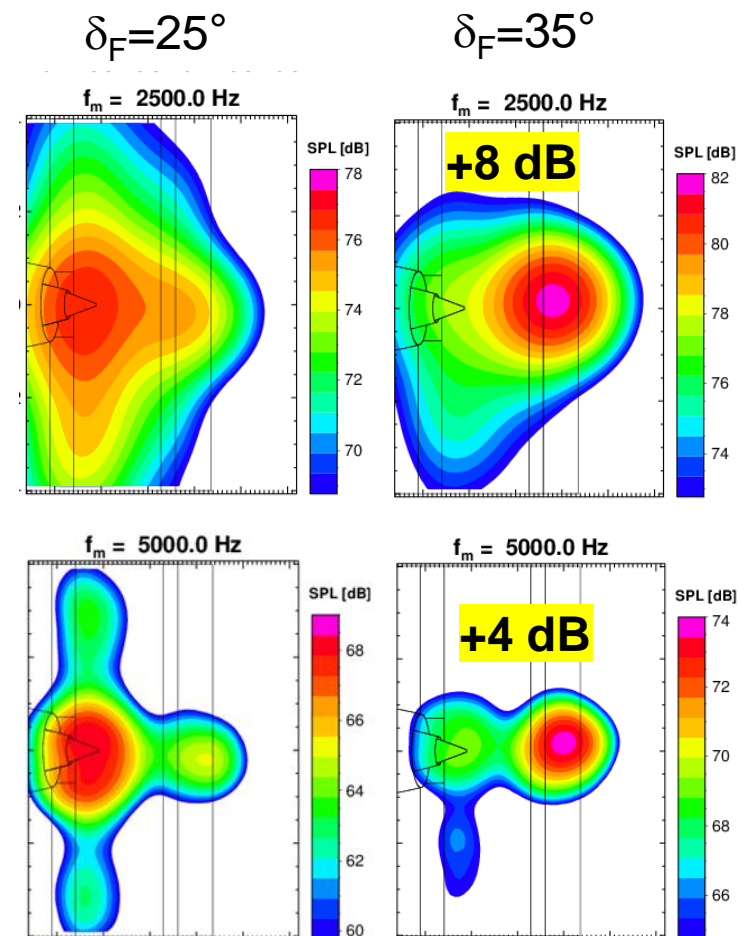
JET-FLAP INTERFERENCE noise

Measurement of JFI noise dual stream nozzle in DLR-AWB (F16 High lift)

flap setting



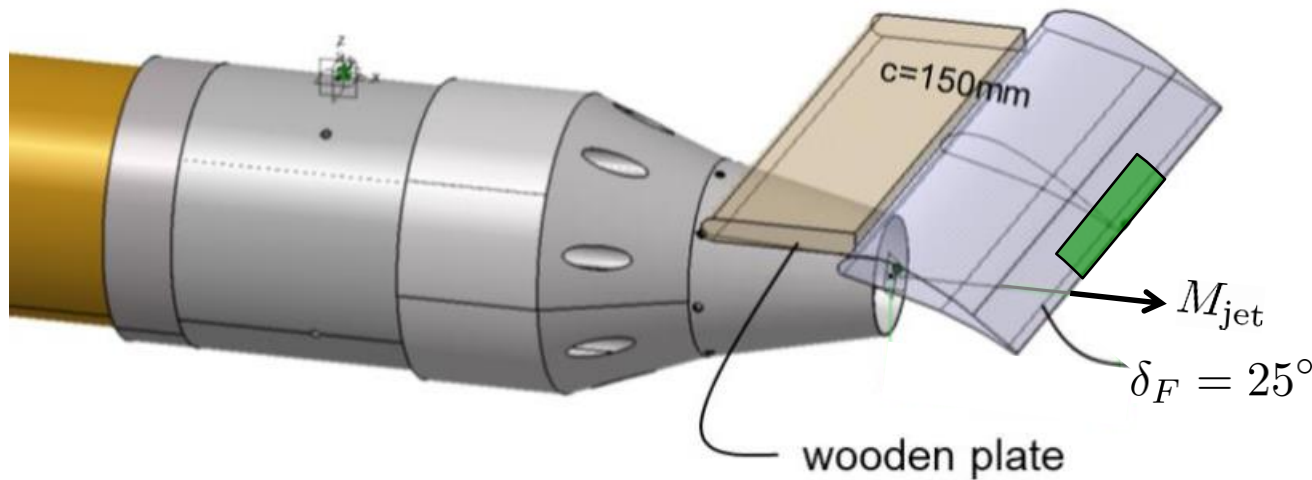
$$U_{\text{Fan}} = 129 \text{ m/s} \quad U_{\text{Core}} = 108 \text{ m/s}$$



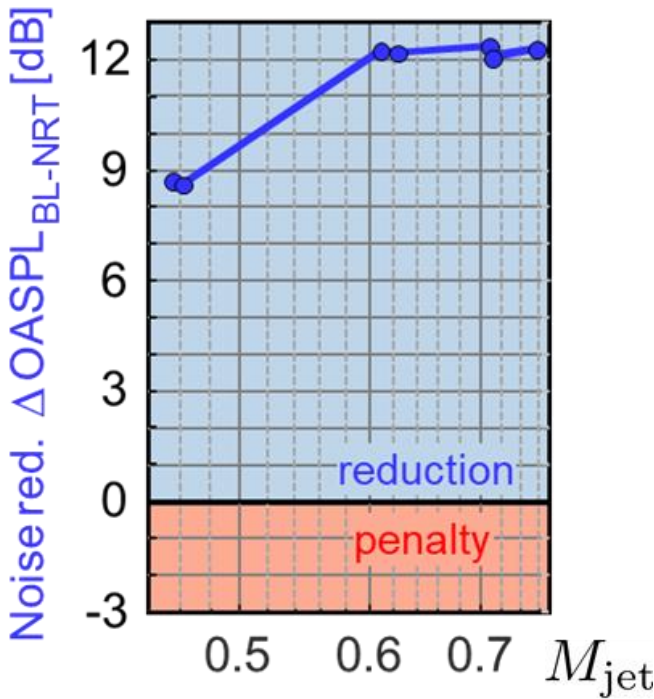
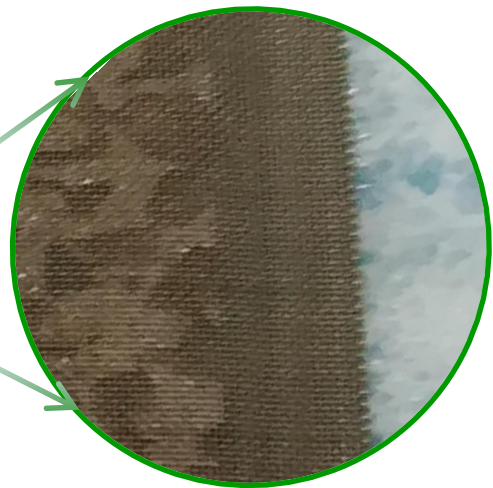
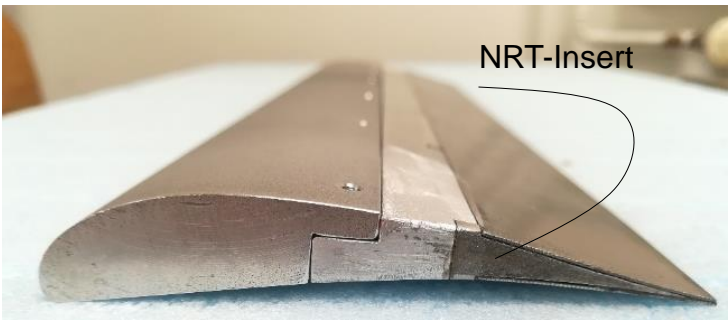
JET-FLAP INTERFERENCE noise reduction



Test of single stream jet combined with F16 flap / effect of porous flap inserts



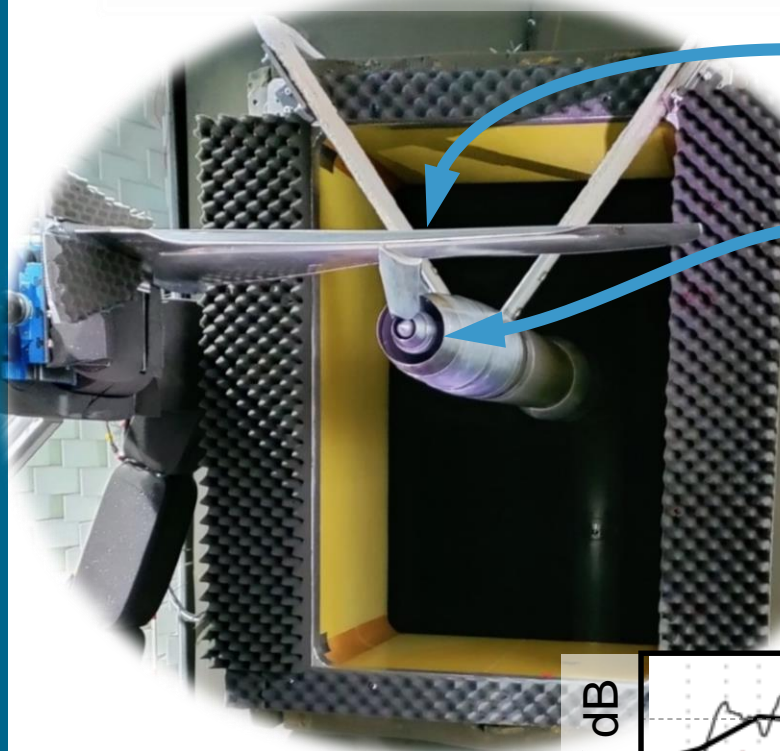
best variant:
coarse porous metal + mesh cover



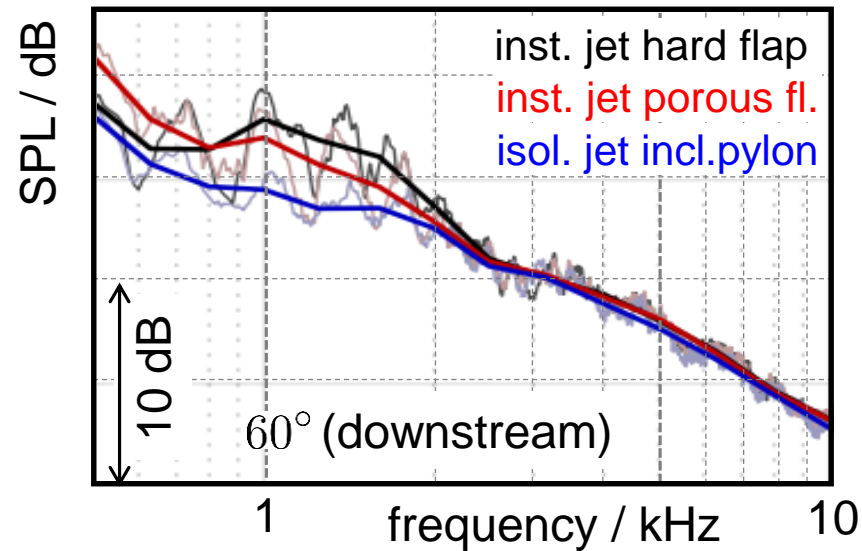
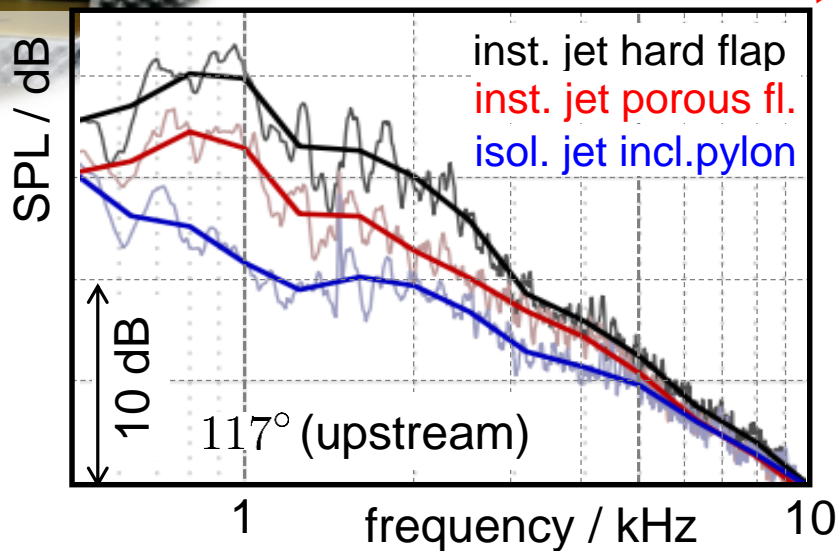
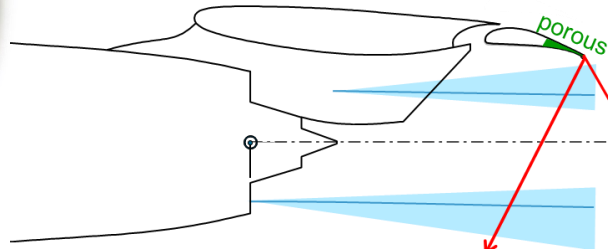
→ appropriate materials
extremely effective



JET-FLAP INTERFERENCE noise reduction



wing model
 AIRBUS RDJ80
 two-element wing flap $\delta_F=14^\circ$
engine model
 SAFRAN dual stream short cowl
 UHBR $A_{Byp}/A_{Core} \sim 7$, $D_{mix} \sim \varnothing 100\text{mm}$



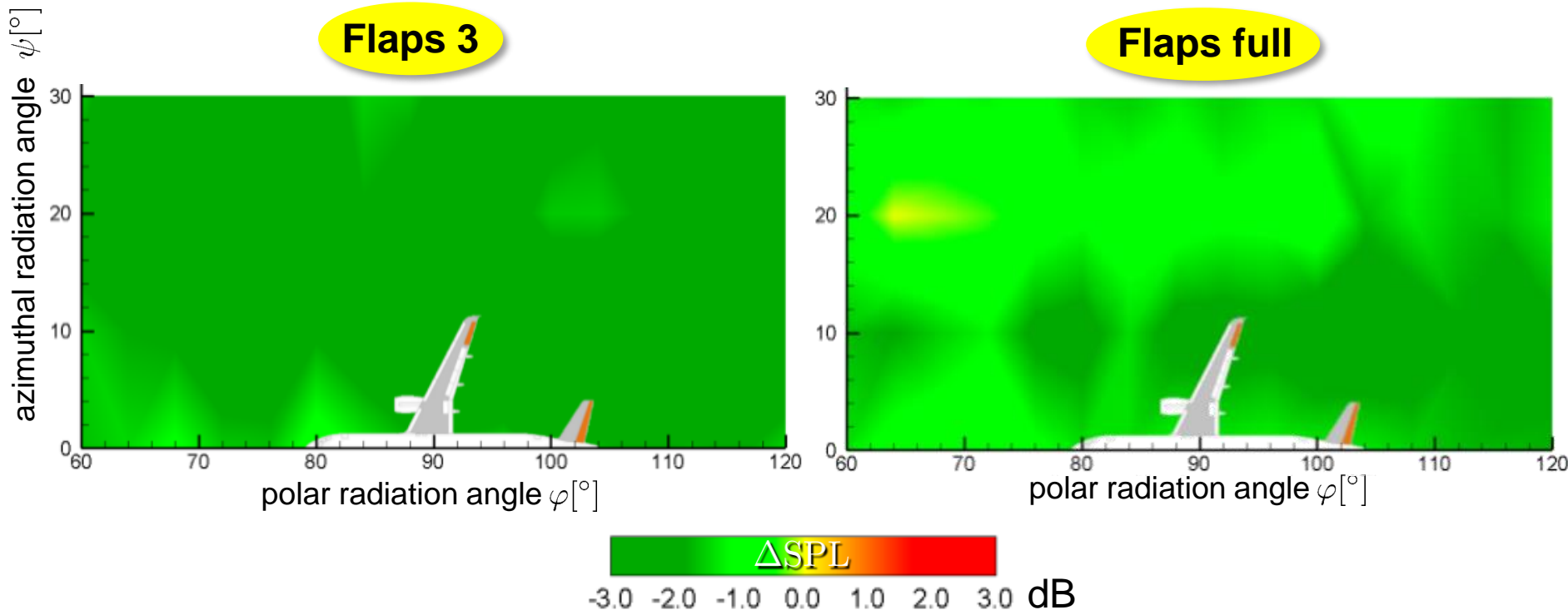
LANDING GEAR – FLAP INTERFERENCE noise



approach– gear down – 135 kts

Flaps 3

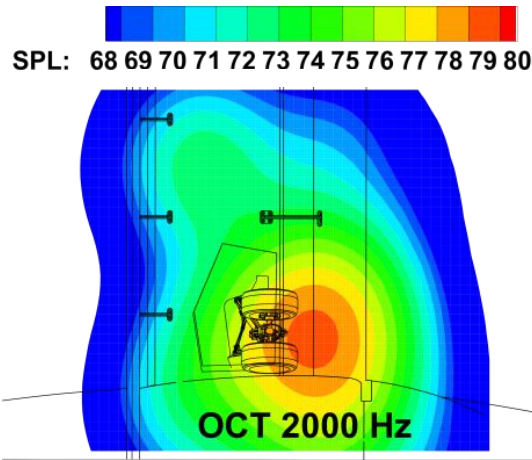
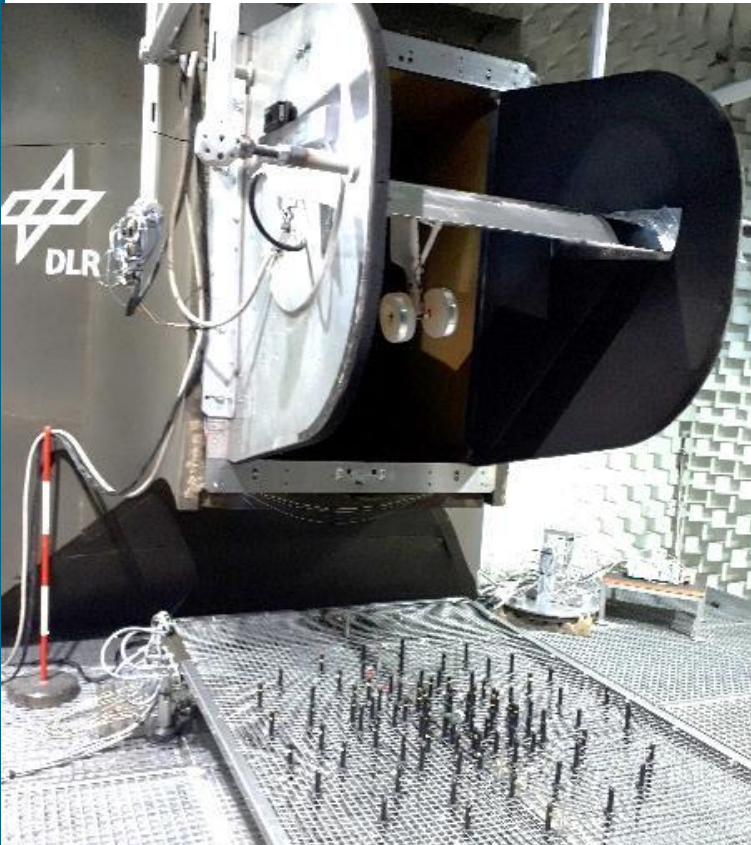
Flaps full



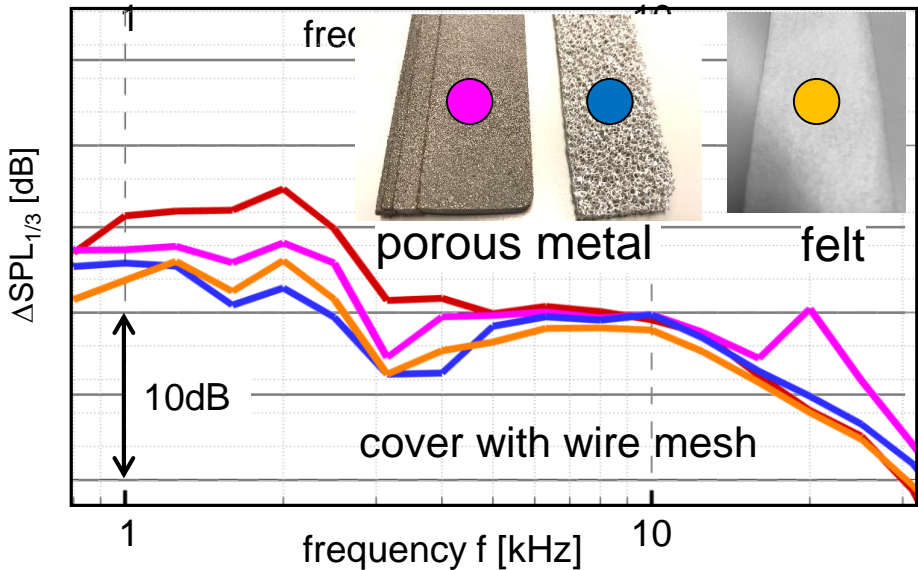
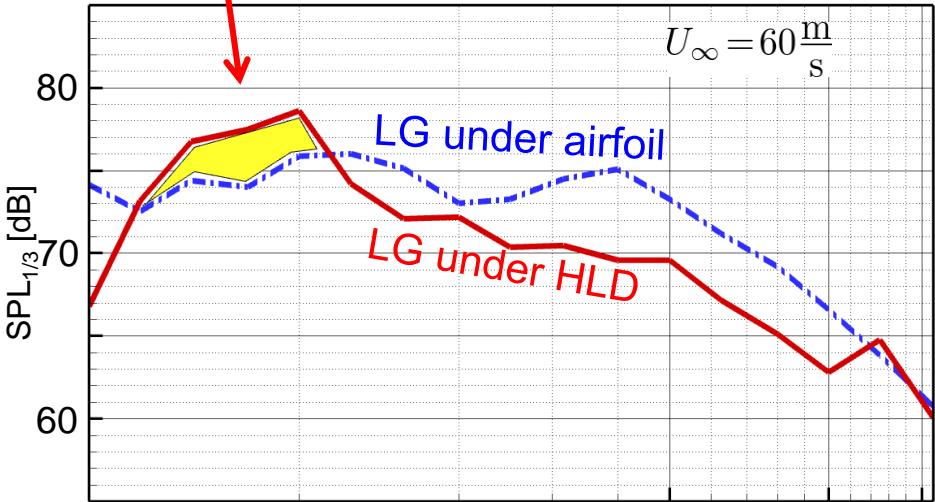
→ at large deployment angle installation excess noise increased

LANDING GEAR – FLAP INTERFERENCE noise

Acoustic Windtunnel studies AWB



Gear wake / flap interaction noise

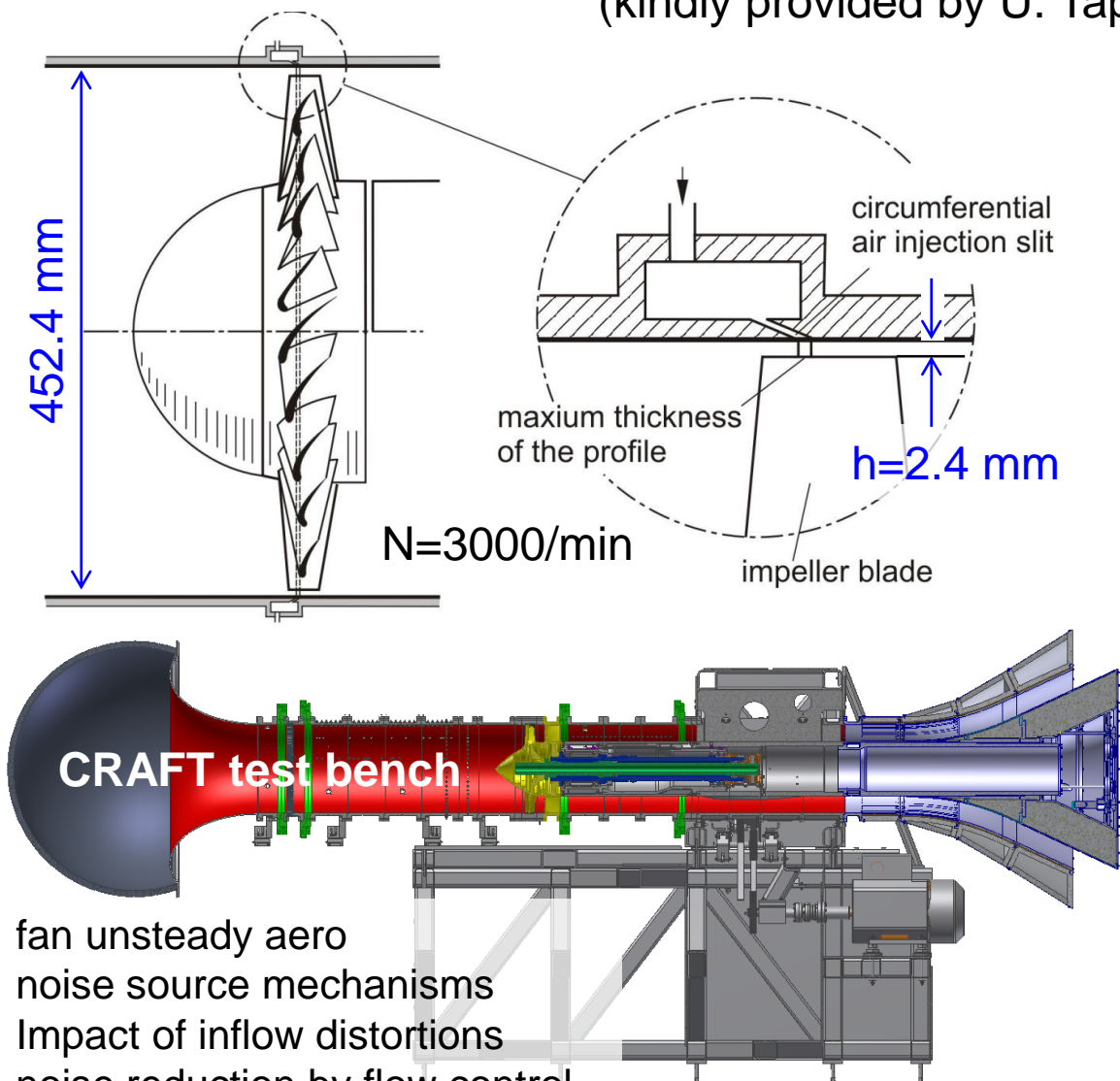


→ significant low frequency noise source at flap leading edge

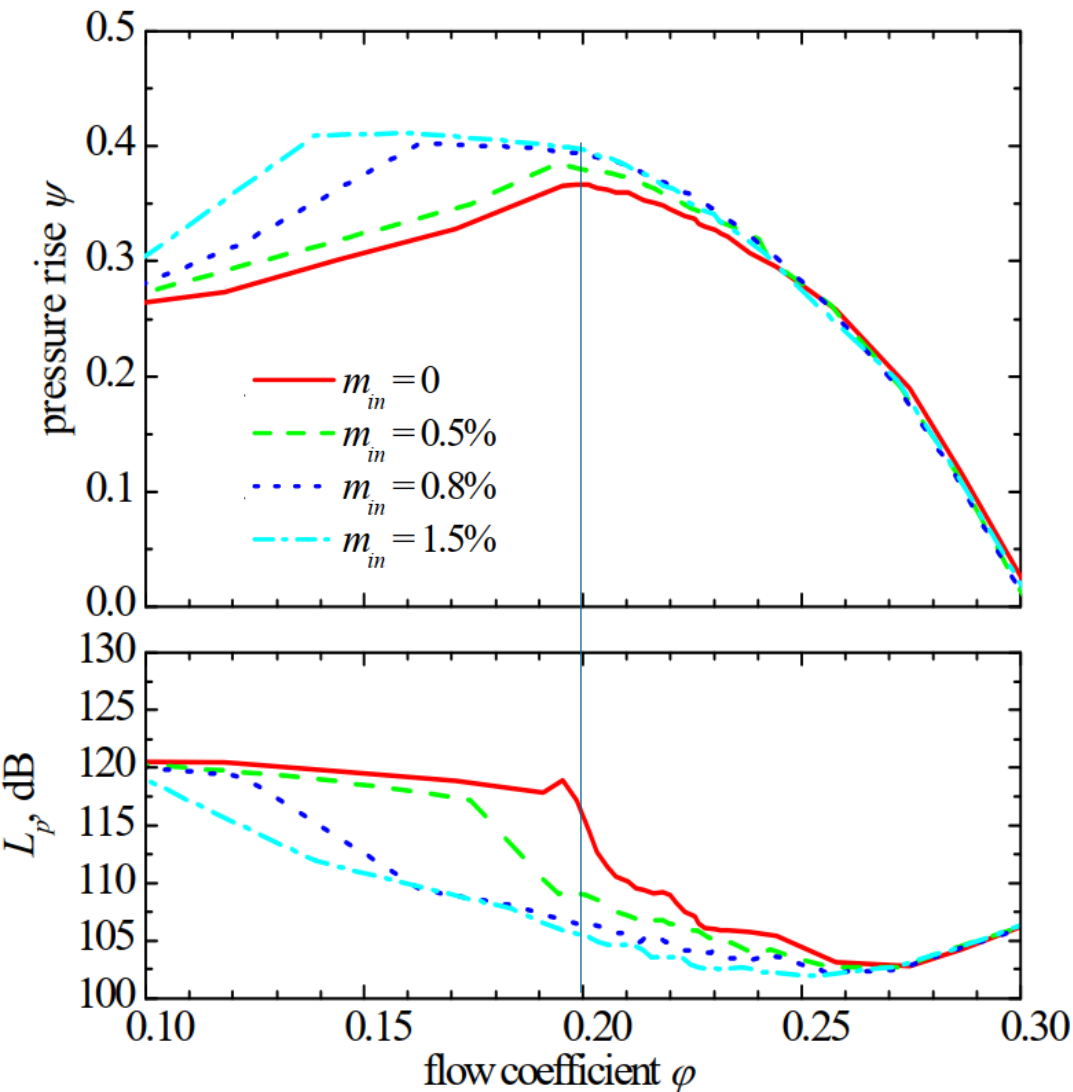
FAN TIP CLEARANCE NOISE - reduction by flow control



(kindly provided by U. Tapken, DLR Institute of propulsion technology)



- fan unsteady aero
- noise source mechanisms
- Impact of inflow distortions
- noise reduction by flow control

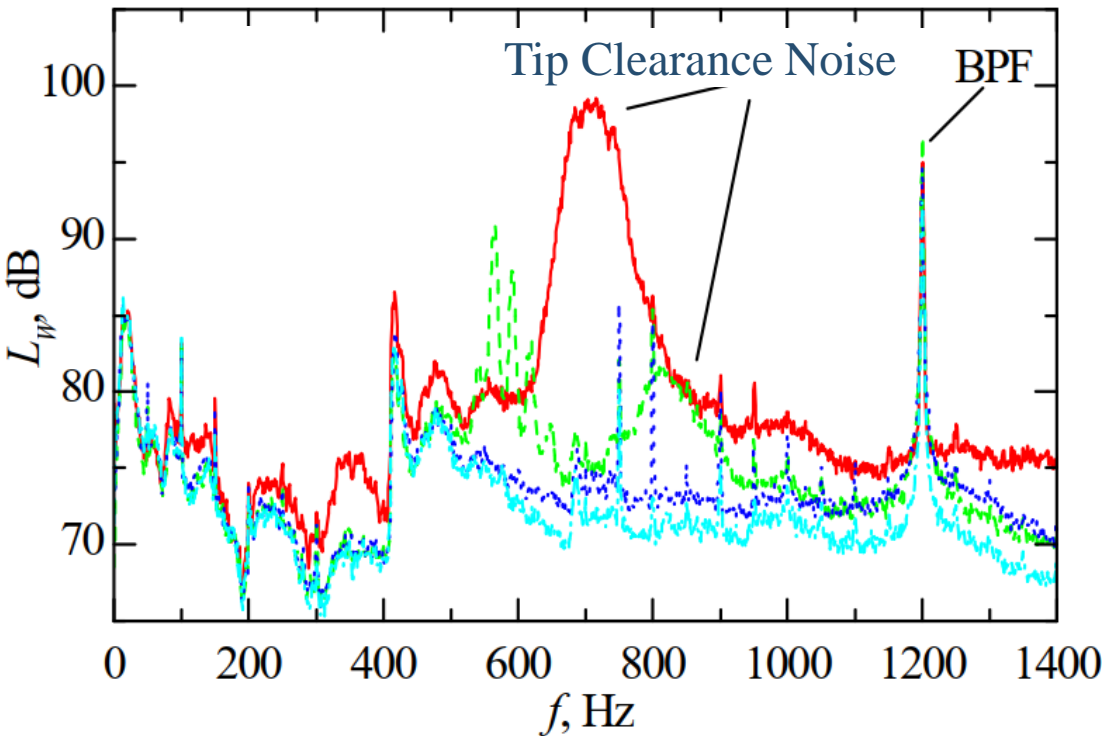


FAN TIP CLEARANCE NOISE - reduction by flow control

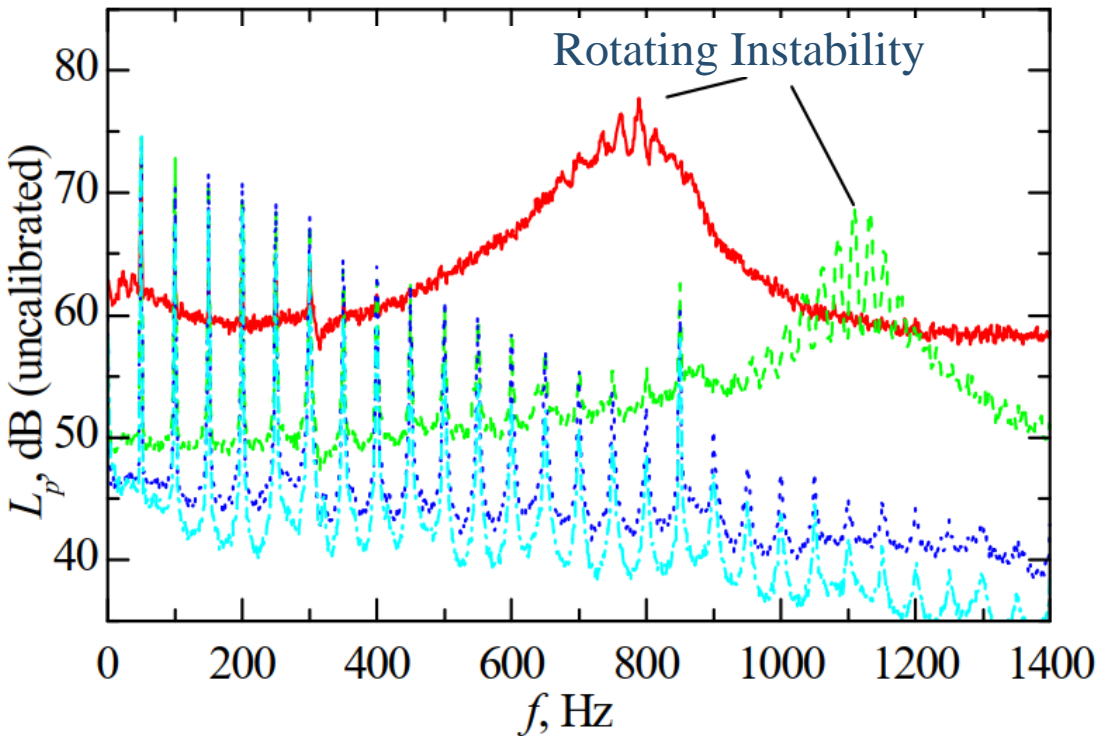


steady air injection at rotating instability operating point ($\varphi=0.2$)

sound power in fan outlet (far-field)



wall pressure on rotor blade suction side



- $m_{in} = 0, \quad \psi = 0.367, \eta = 0.736$
- $m_{in} = 0.5\%, \psi = 0.376, \eta = 0.738$
- ... $m_{in} = 0.8\%, \psi = 0.383, \eta = 0.751$
- .-. $m_{in} = 1.5\%, \psi = 0.394, \eta = 0.731$

noise reduction technologies - conclusions

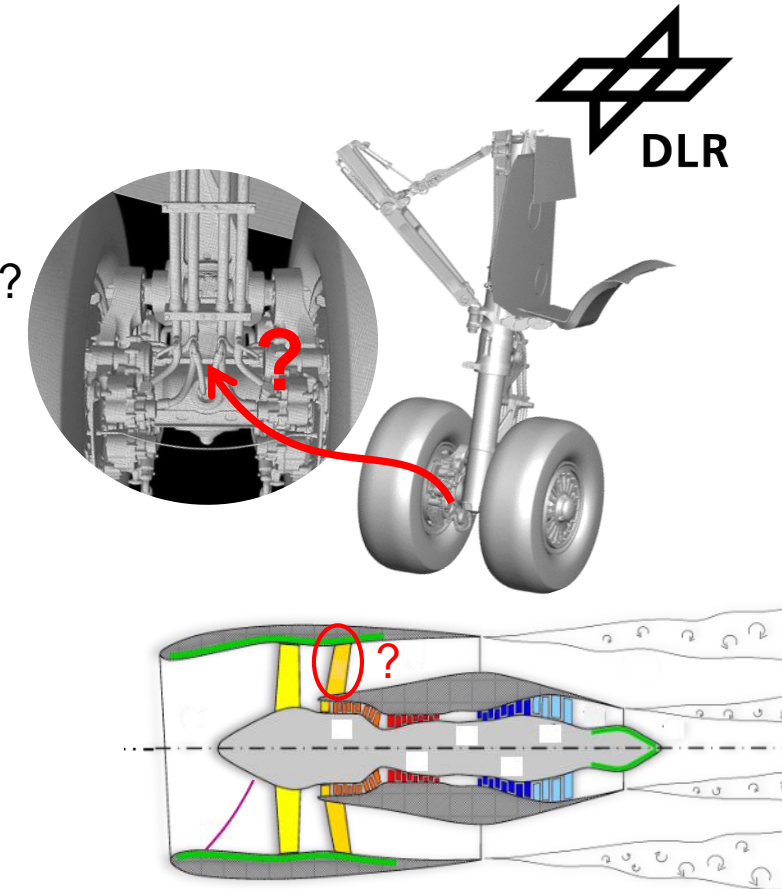


effective aeronoise reduction may be achieved by

- aero-shaping But: how to arrive at „best shape“ in MD context?
- materials But: what are „best properties“?
 - with existing materials
 - modified materials (graded, anisotropic)
 - newly designed materials, i.e. tailored (meta) materials
- flow control But: what is the most effective/efficient way of air injection?

Source noise localization & quantification – a pre-requisite for low noise design –

- Where exactly happens the sound **generation** inside a complex structure ?
- How unique are beamforming maps ?
- Sound **generated** at installed components ?
- What is a „source of sound“ at all?
→ Can one define a „surface source quantity“?
- Can one extract a „source indicator“ without propagation to the farfield ?
- Can one overcome assumptions in beamforming and do localization based on first principles ?

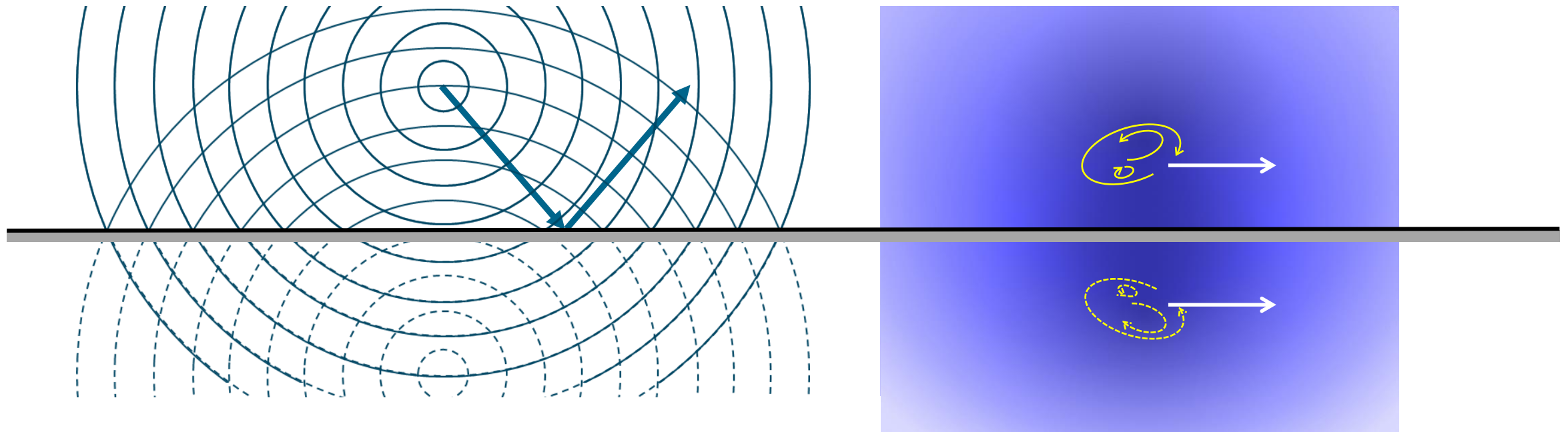


- special thanks to ebmpapst for cooperation on this -

Concept for alternative source localization – source hypothesis



no sound **generation** by pure **reflection** of an incident pressure field



Concept for alternative source localization – translation to math



Ffowcs-Williams & Hawkings (Kirchhoff) equation, solid surface
(low Mach no., freq. domain):

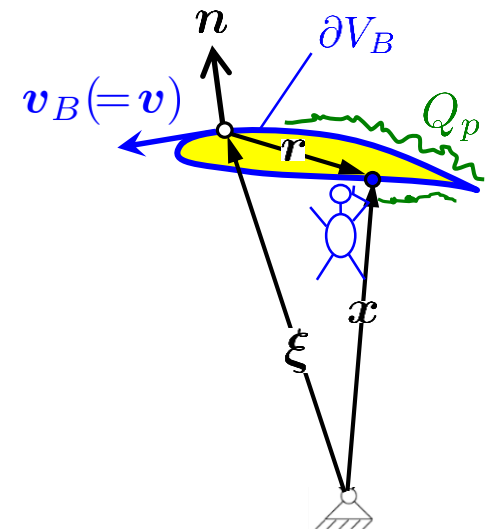
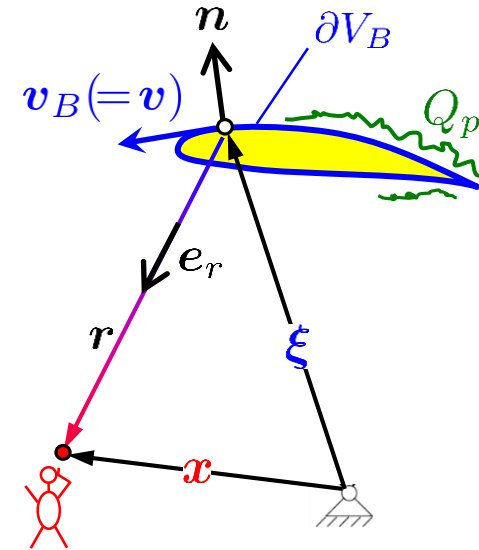
$$\hat{p}(\mathbf{x}) = \hat{p}_f(\mathbf{x}) + \frac{1}{4\pi} \int_{\partial V_B} \exp(-ikr) \left[(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p}(\boldsymbol{\xi}) - \frac{1}{r} \frac{\partial \hat{p}}{\partial n} \right] dS(\boldsymbol{\xi}) \approx 0$$

$$\hat{p}_f(\mathbf{x}) = \frac{1}{4\pi} \int_{V_\infty^+} \frac{\hat{Q}_p^{\text{LH}}}{r} \exp(-ikr) dV(\boldsymbol{\xi}) \quad \text{free field signature of volume sources}$$

Choose reception point \mathbf{x} on surface:

$$\hat{p}(\mathbf{x}) = 2\hat{p}_f(\mathbf{x}) + \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr) (ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p}(\boldsymbol{\xi}) dS(\boldsymbol{\xi})$$

↑
solve for

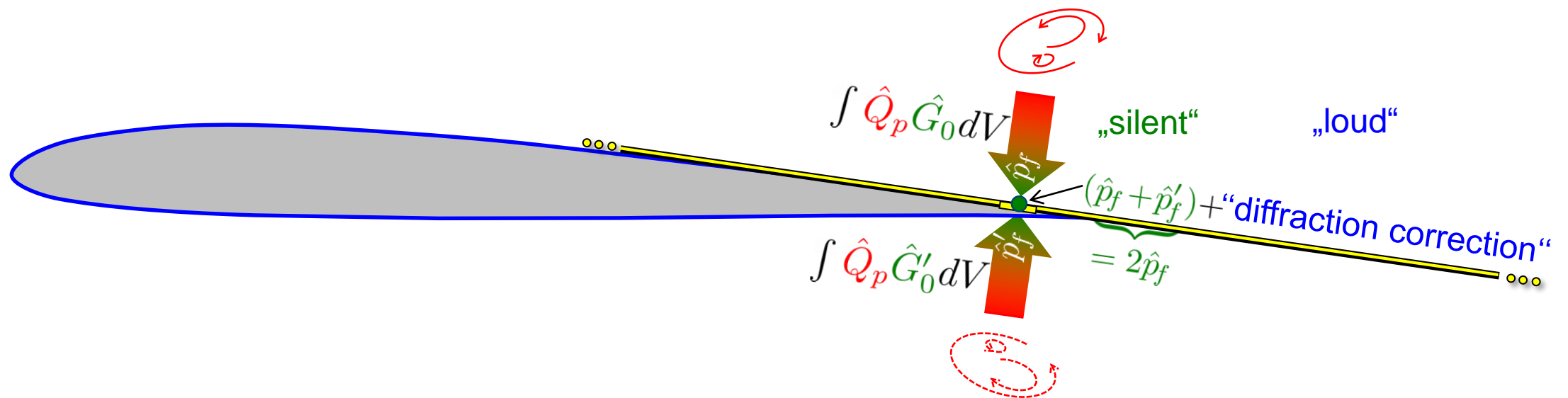


Concept for alternative source localization – reading the equation

no sound **generation** by pure **reflection** of incident pressure field \hat{p}_f

⇒ source of sound on surfaces is **pure diffraction** of pressure field

$$\hat{p}(\mathbf{x}) = 2\hat{p}_f(\mathbf{x}) + \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p} dS(\xi)$$



Acoustic surface pressure \hat{p}_S and the surface source \hat{q}

$$\hat{p}(\mathbf{x}) = 2\hat{p}_f(\mathbf{x}) + \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p} dS(\xi)$$

$\hat{p} = \hat{p}_S + 2\hat{p}_f$

$$\hat{p}(\mathbf{x}) - 2\hat{p}_f(\mathbf{x}) = \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p} dS(\xi)$$

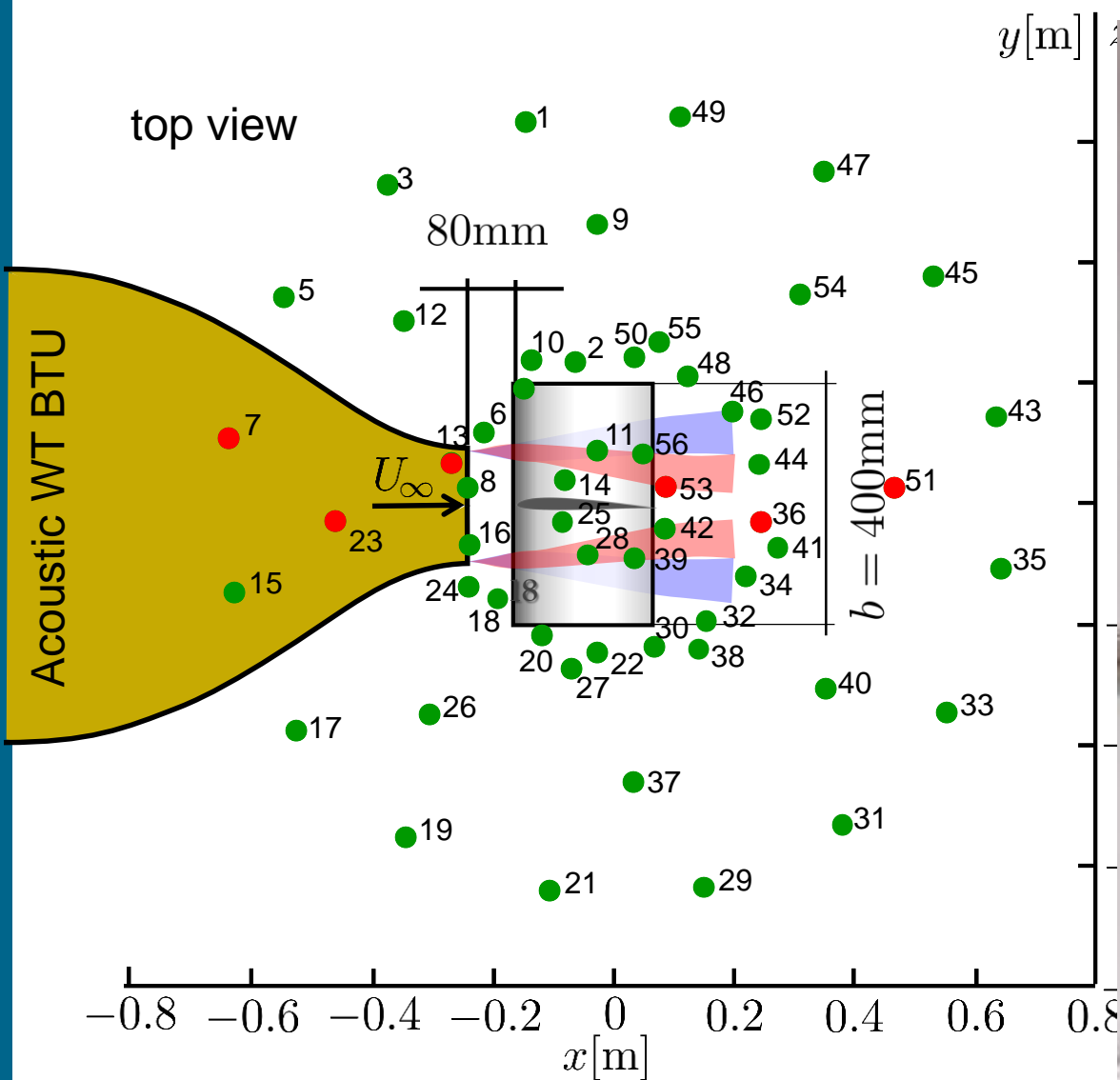
$$\Rightarrow \hat{p}_S(\mathbf{x}) = 2\hat{q} + \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p}_S(\xi) dS(\xi) \quad (\text{Kirchhoff equation})$$

$$\hat{q}(\mathbf{x}) = \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{p}_f(\xi) dS(\xi)$$

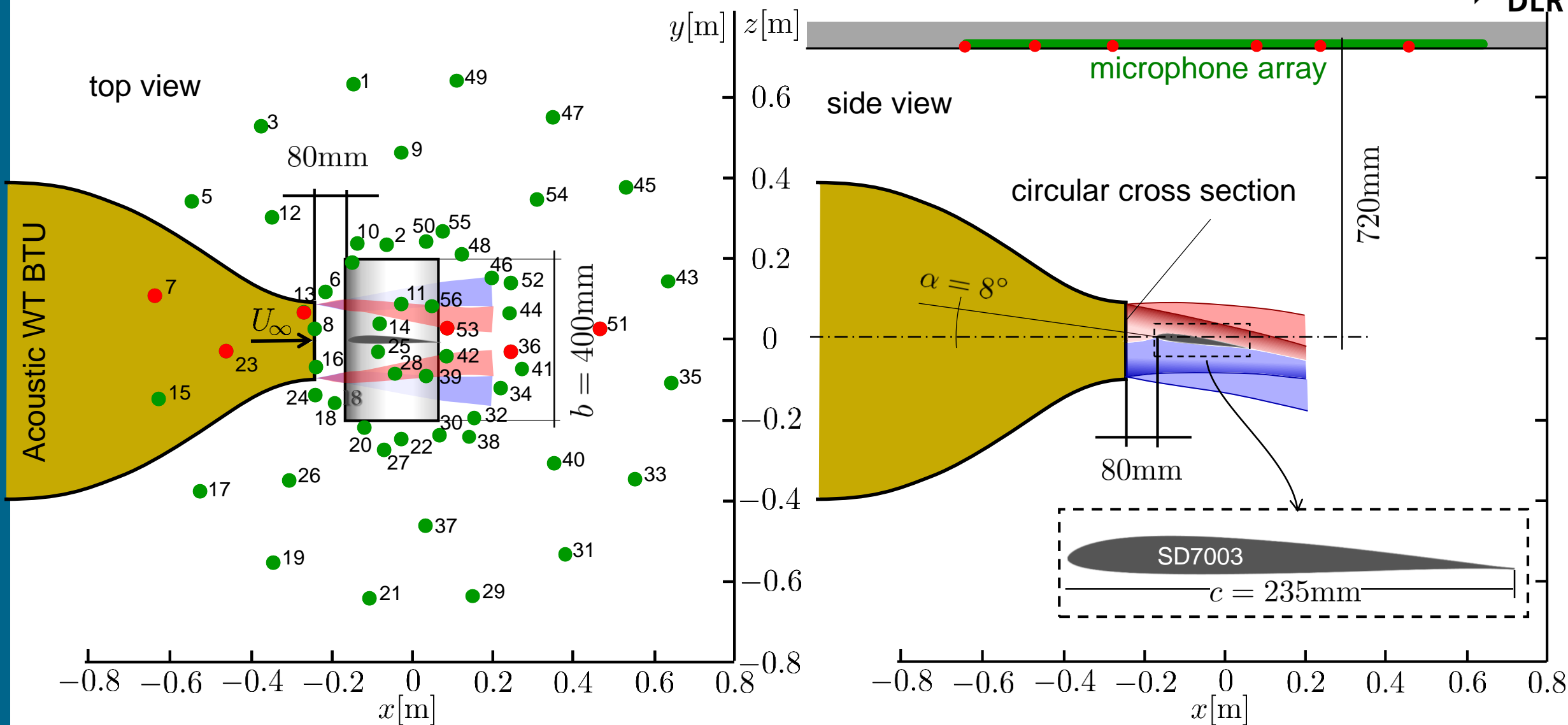
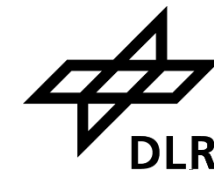
$\Leftrightarrow \hat{p}_S$ is physically realizable pressure field

$$F_d[\hat{(\cdot)}] = \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr + 1) \frac{\mathbf{e}_r \cdot \mathbf{n}}{r^2} \hat{(\cdot)} dS(\xi)$$

Test case airfoil edge noise



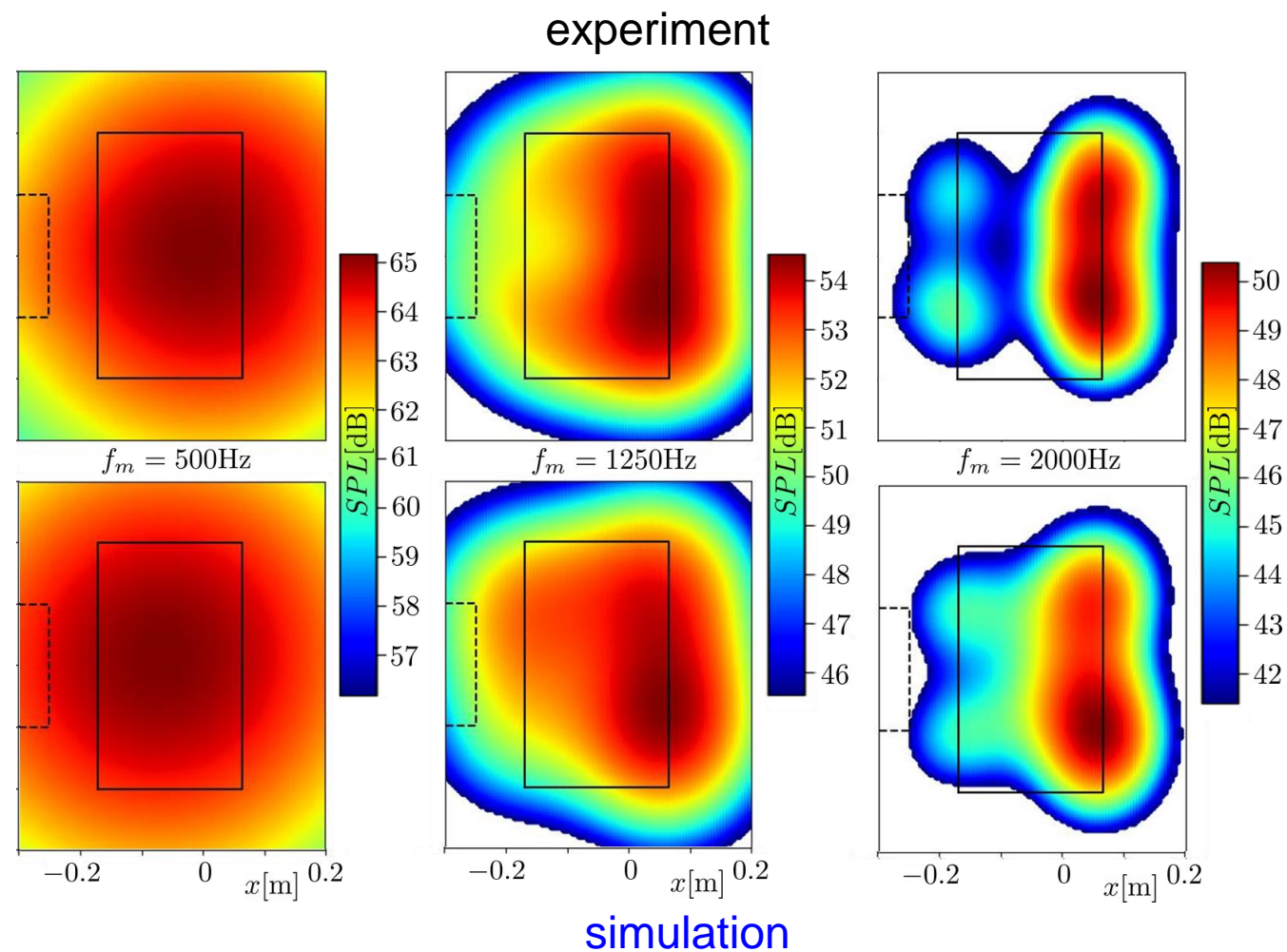
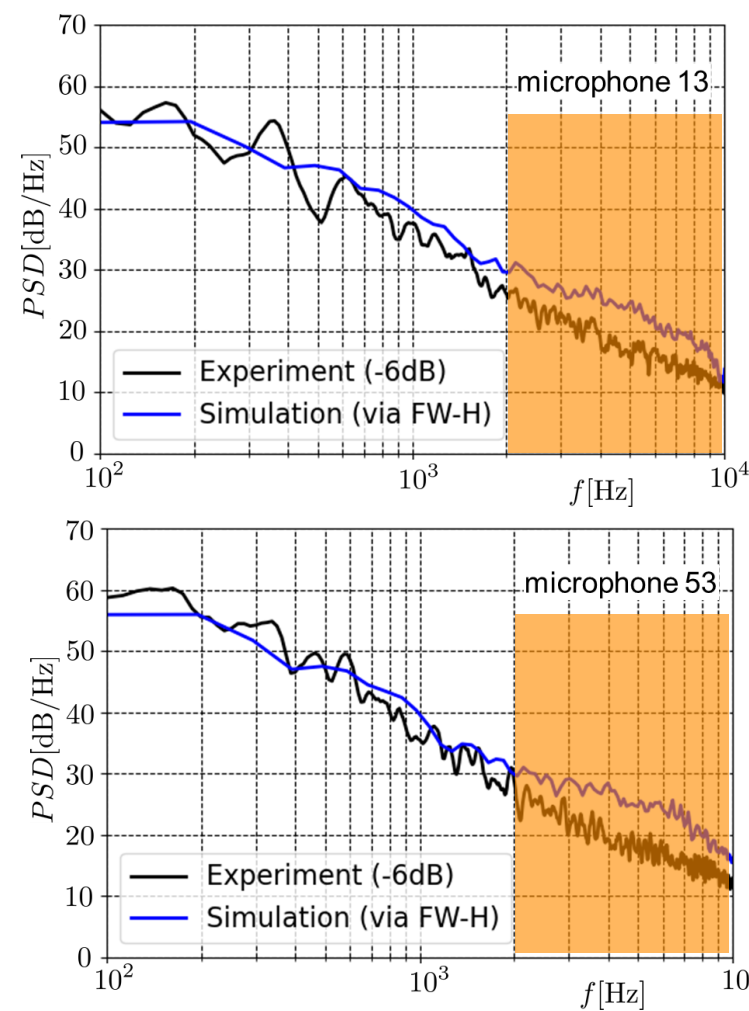
Test case airfoil edge noise



Test case airfoil edge noise – simulation data base



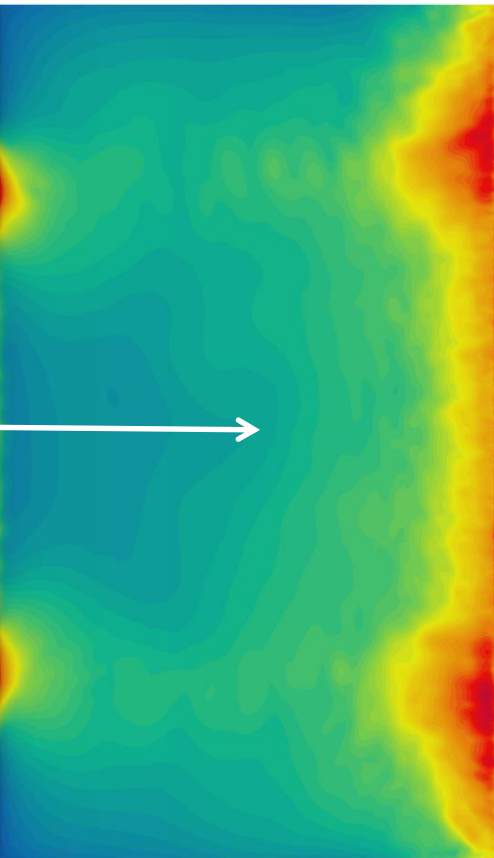
SRS/FW-H results, 23M polyeder cells, Siemens Star-CCM+, courtesy of ebm-papst



Results: acoustic surface pressure \hat{p}_S



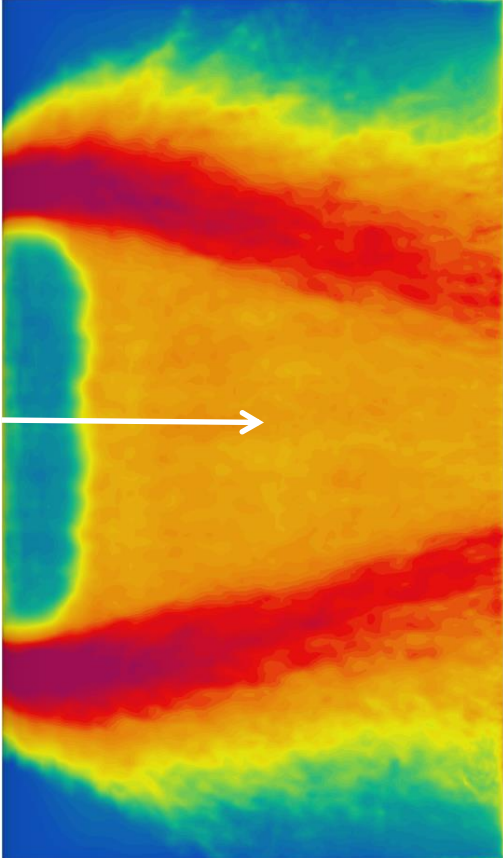
2000Hz



\hat{p}_S

$SPL(m) = 88\text{dB}$

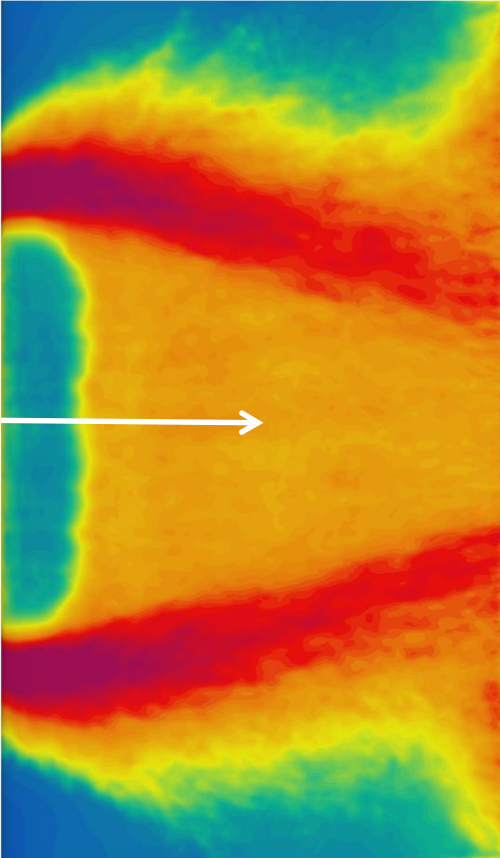
=



\hat{p}

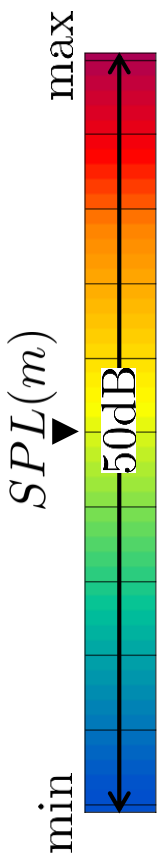
$SPL(m) = 94\text{dB}$

-

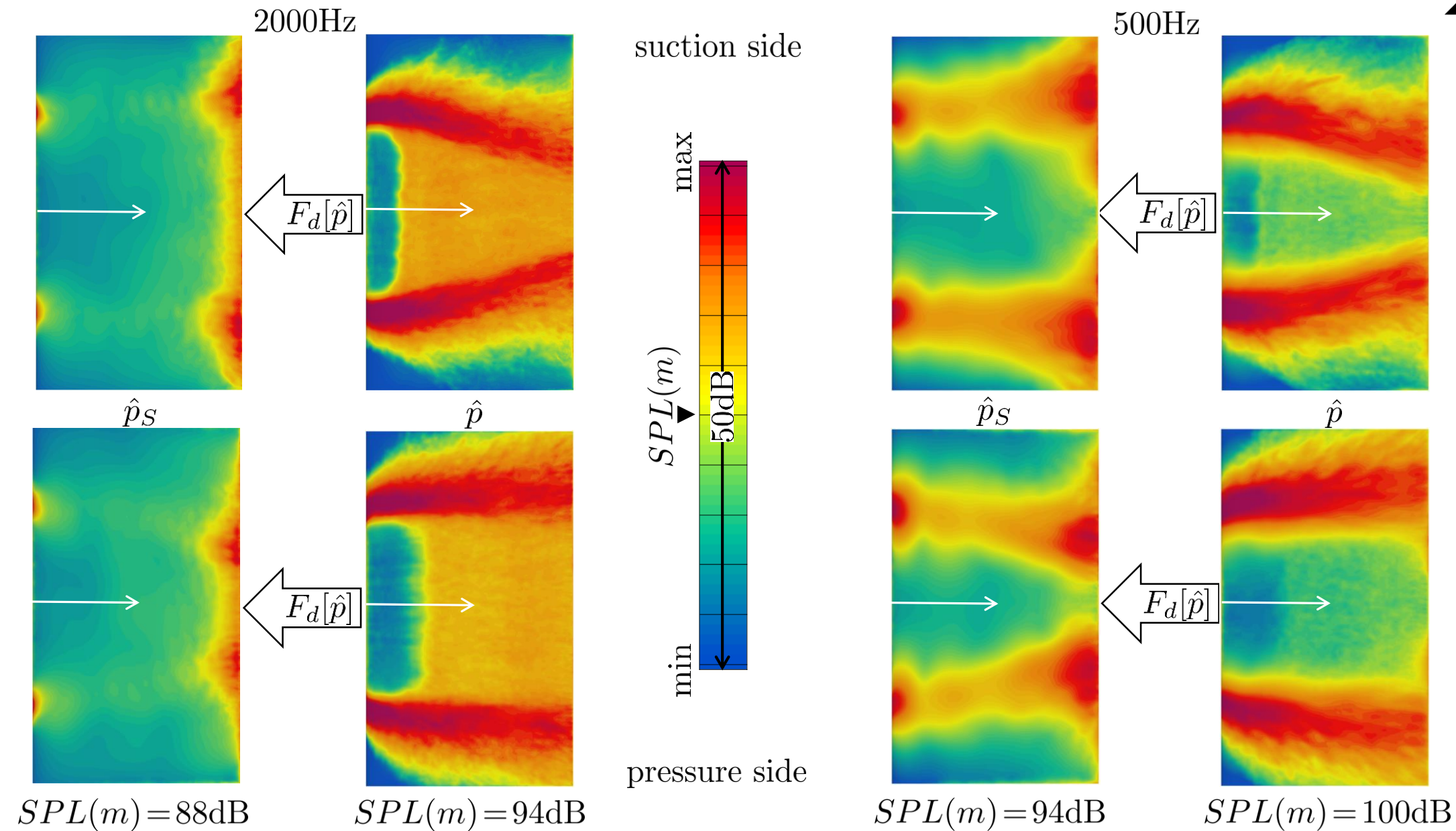


$2 \times \hat{p}_f$

suction side

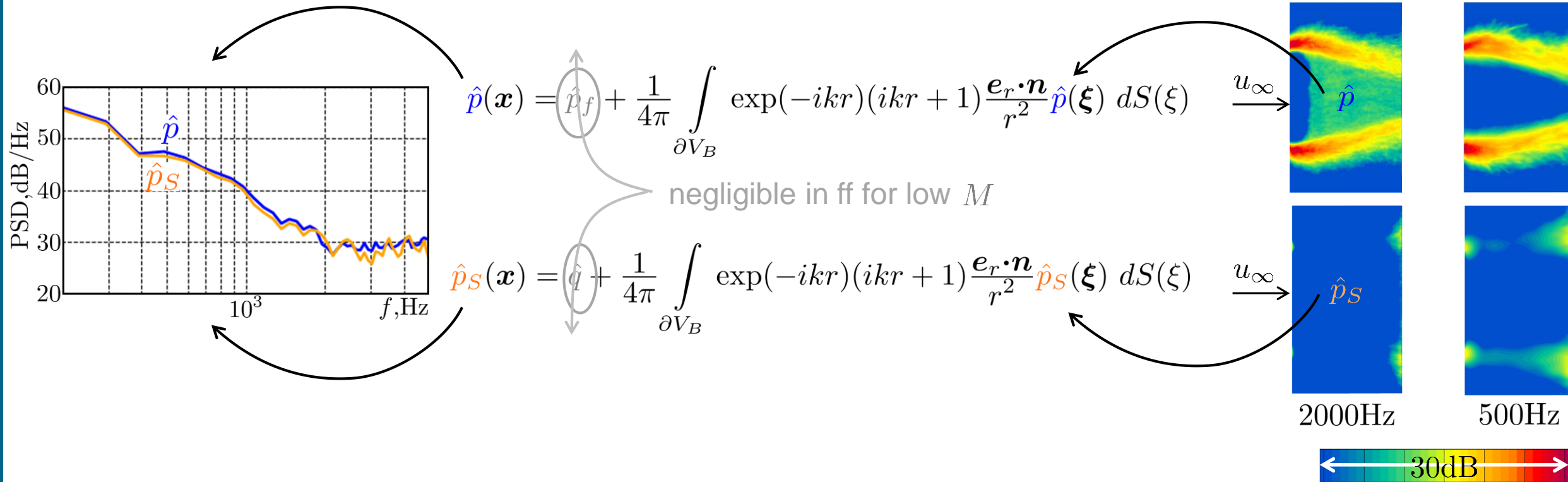


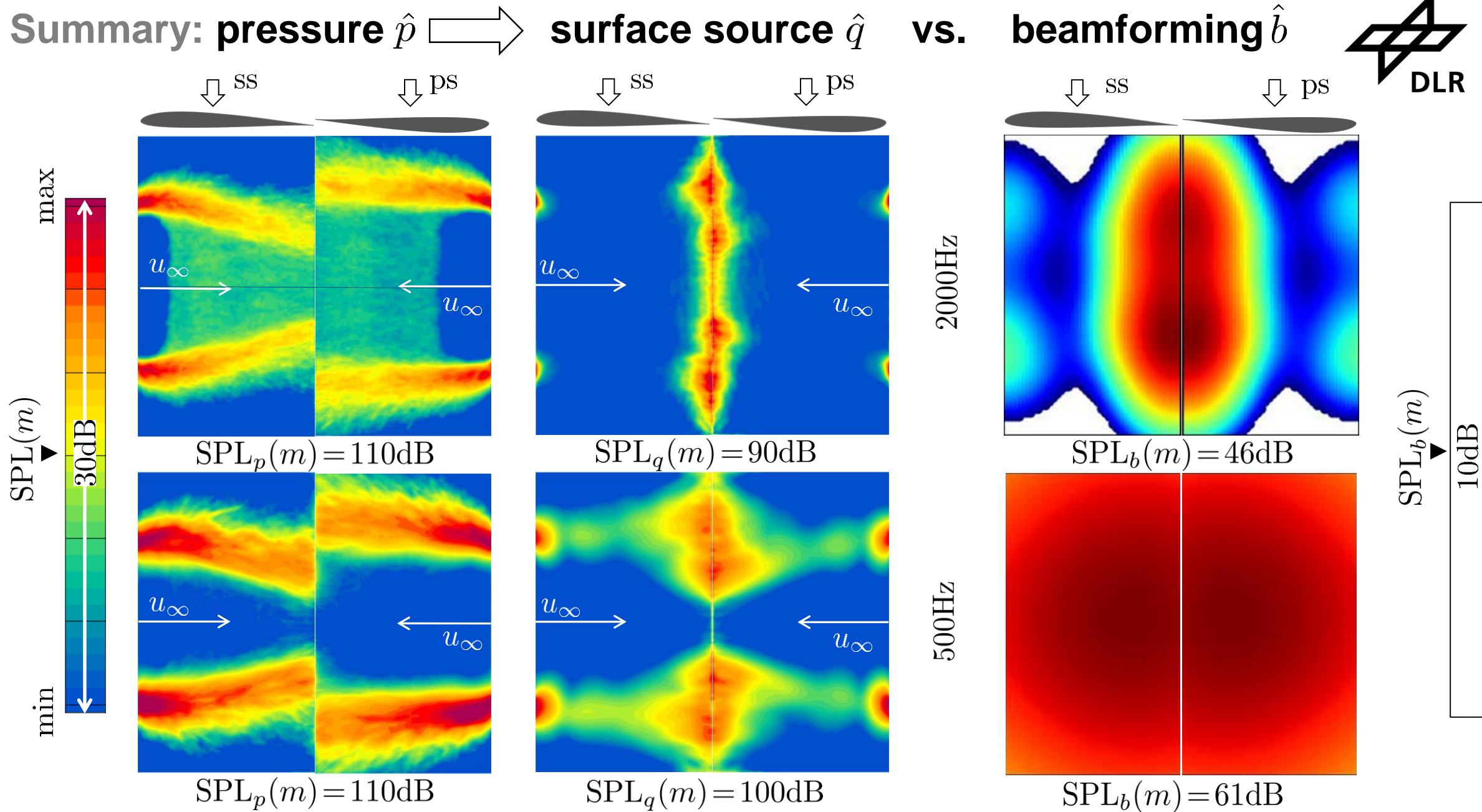
Results: acoustic surface pressure \hat{p}_S



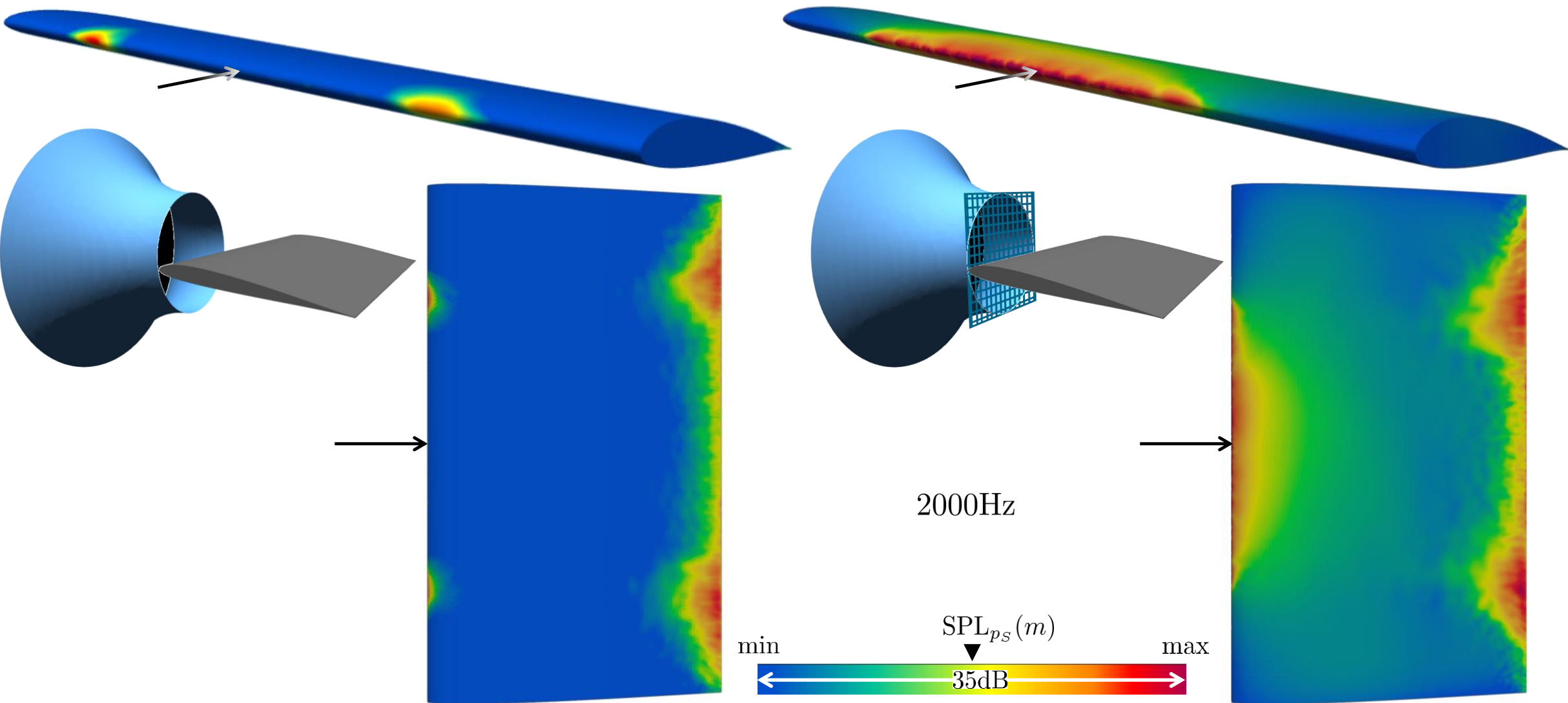
Concept validation – acoustic surface pressure

Does \hat{p}_S carry the source information of the original surface pressure \hat{p} ?

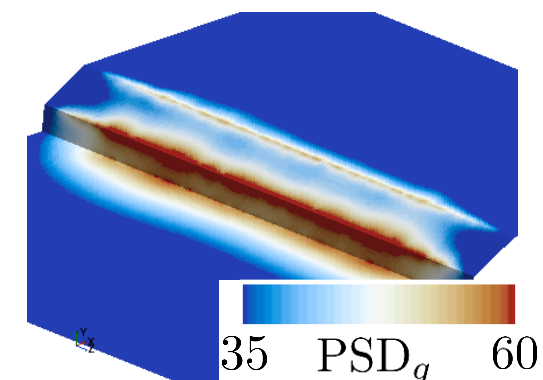
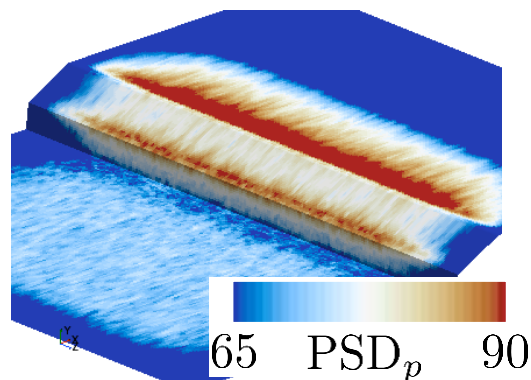
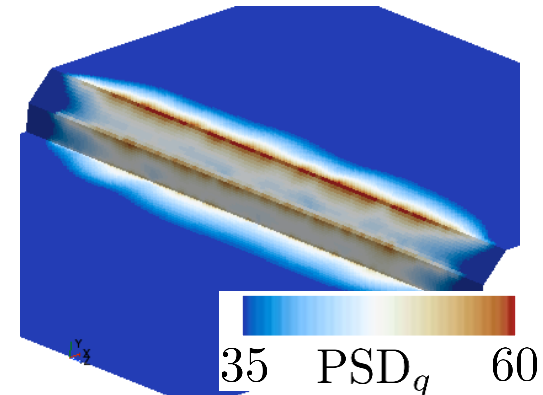
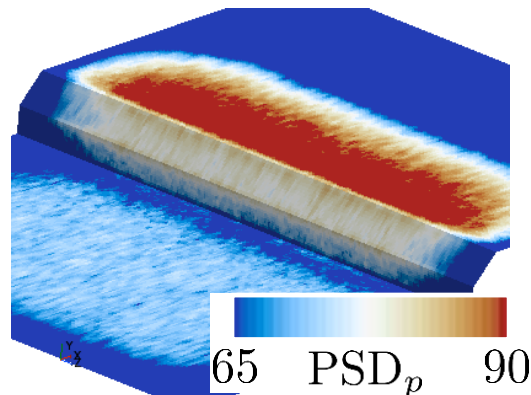
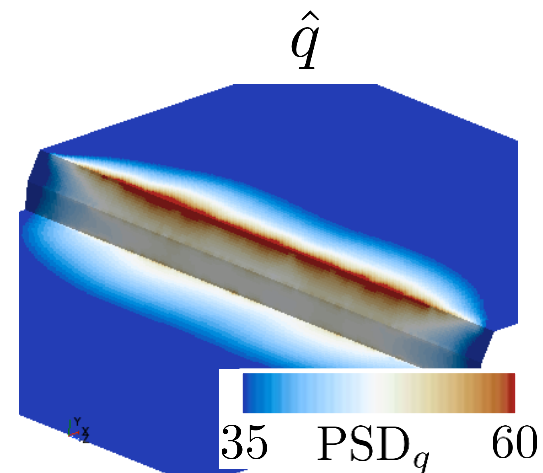
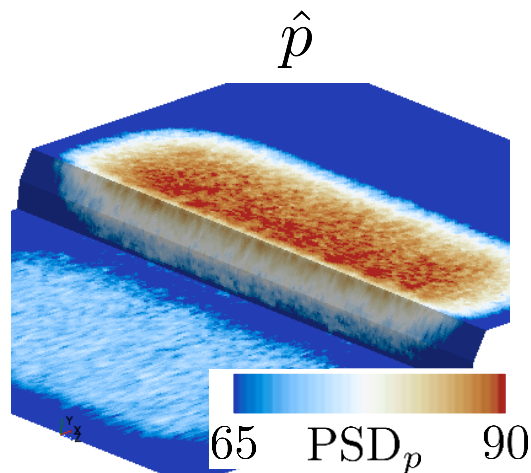
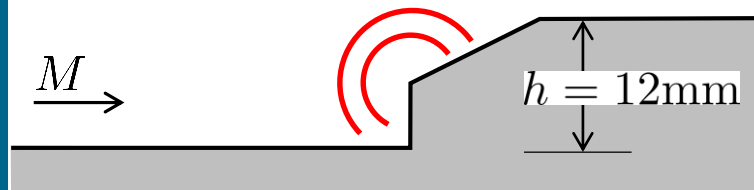
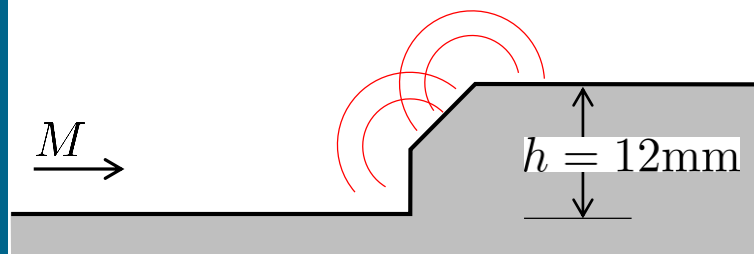
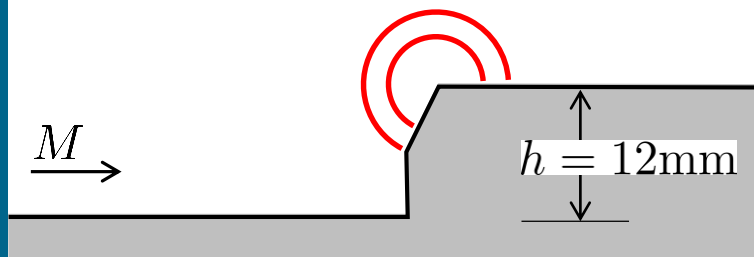




Leading edge noise from inflow turbulence - \hat{p}_S



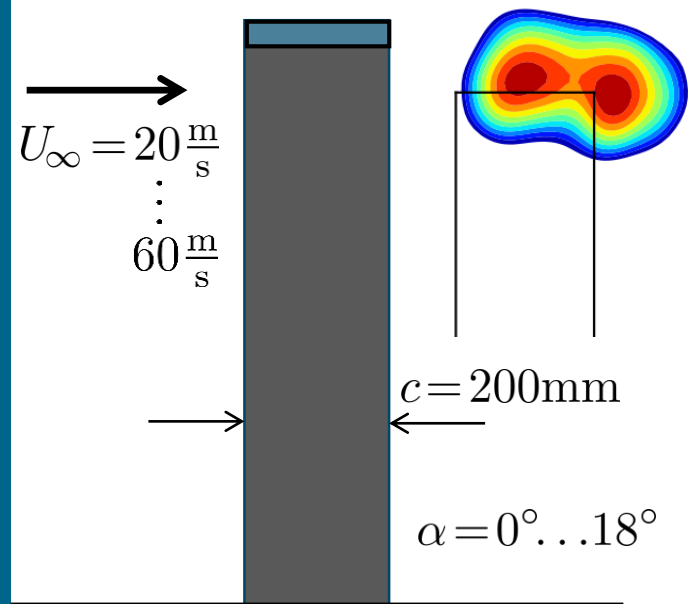
Some more edges...



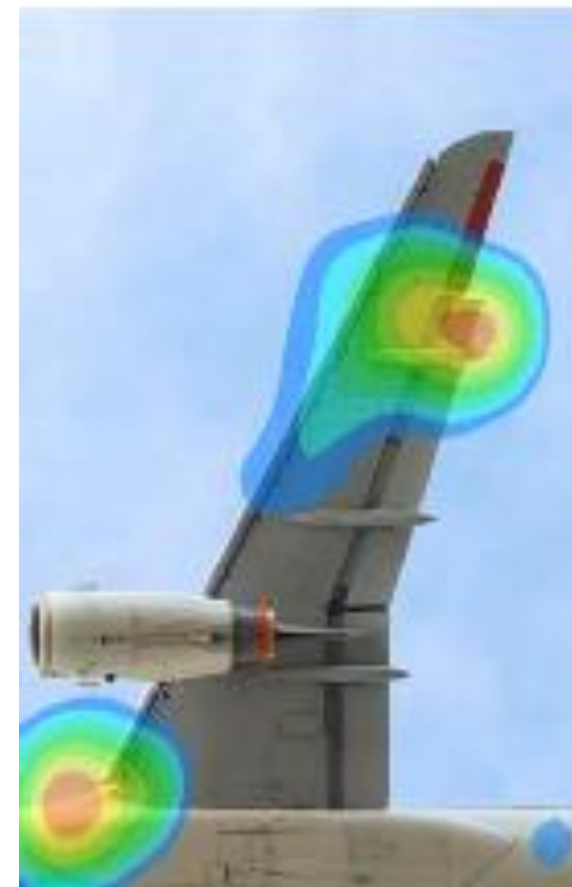
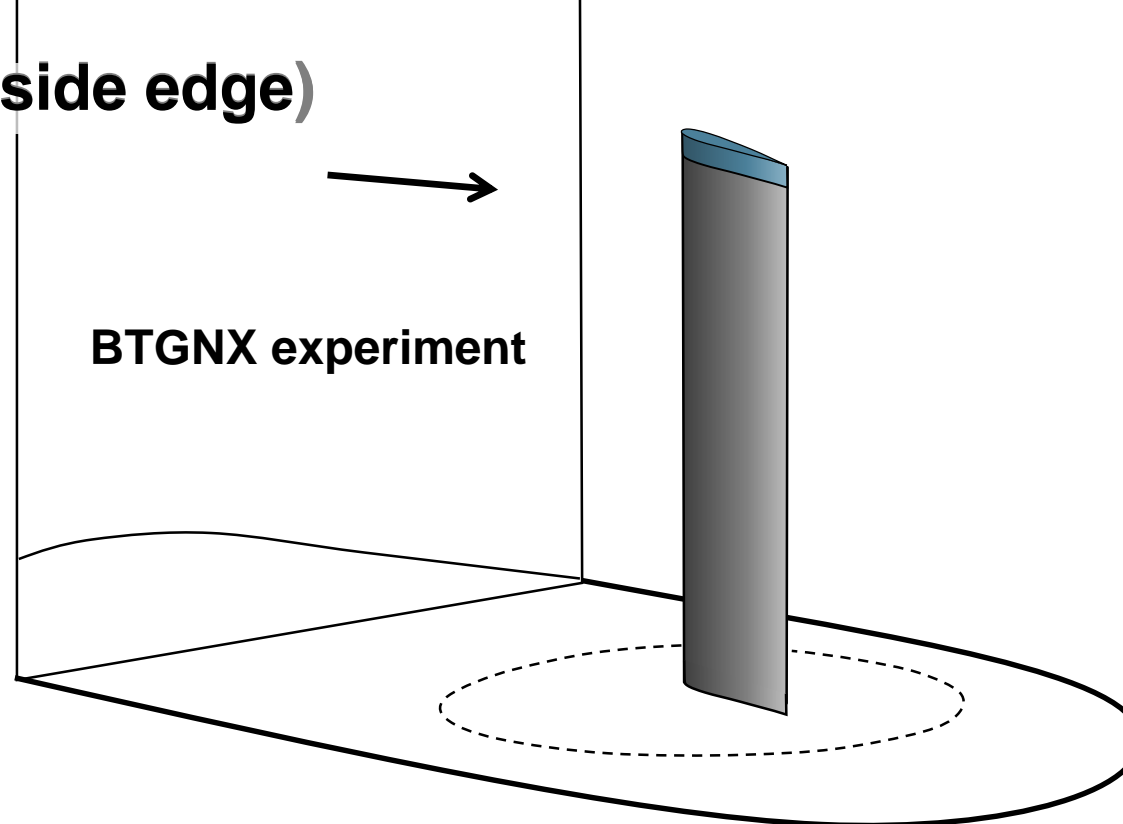
$Re_h = 30000$
 $M = 0.11$
 4000Hz

acoustically compact up to $\approx 28\text{kHz}$!

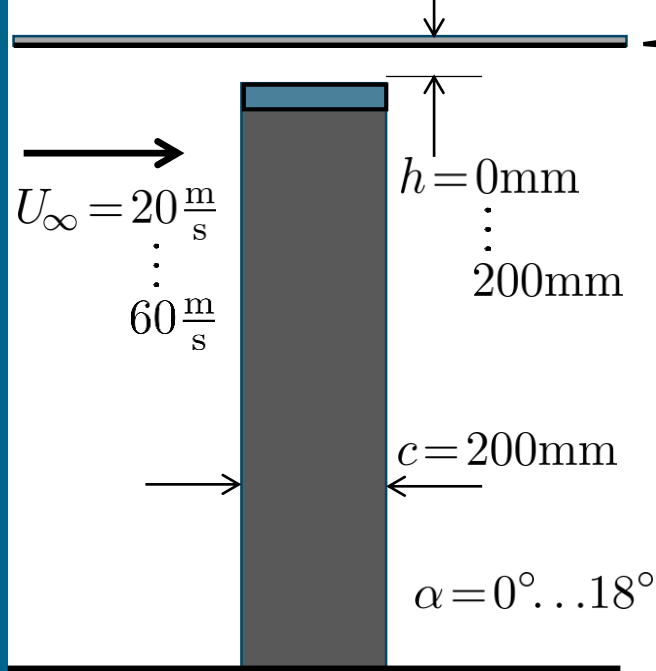
Tip gap noise (flap side edge)



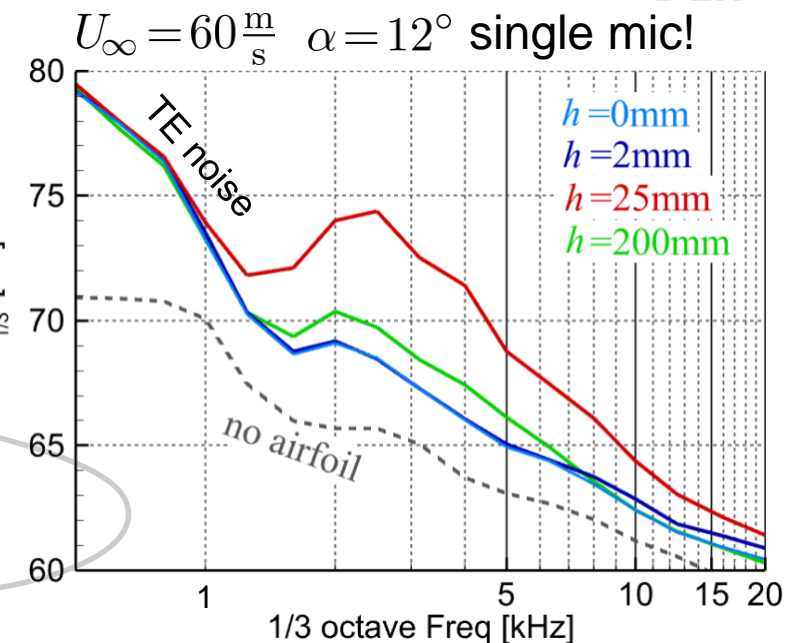
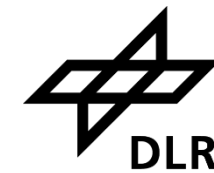
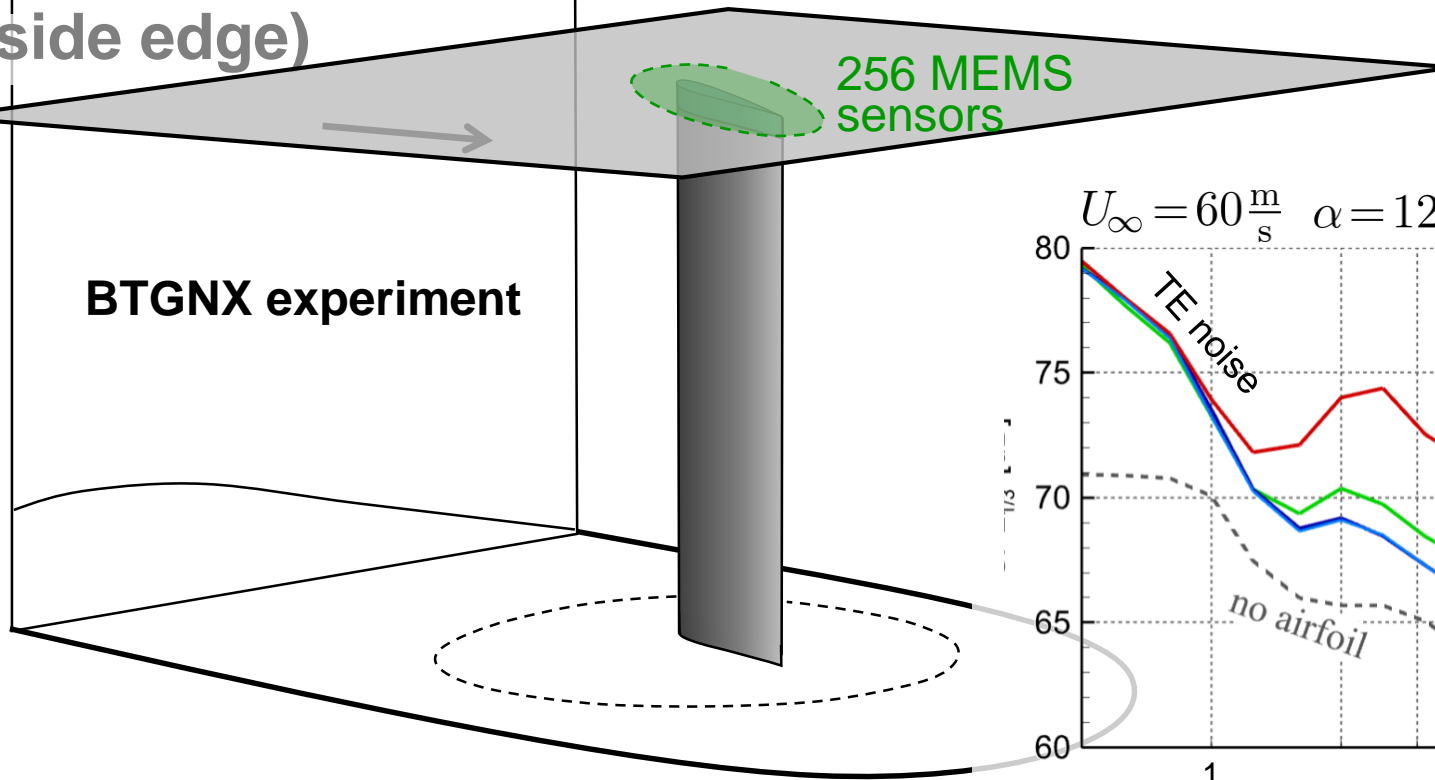
BTGNX experiment



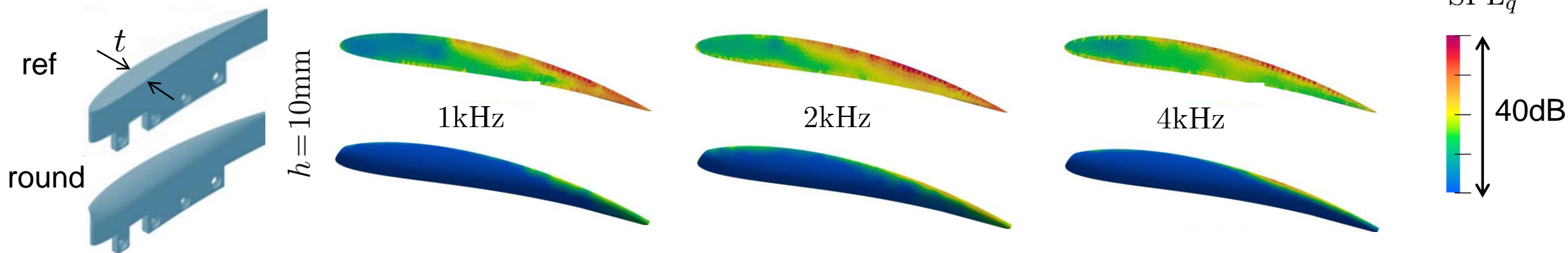
Tip gap noise (flap side edge)



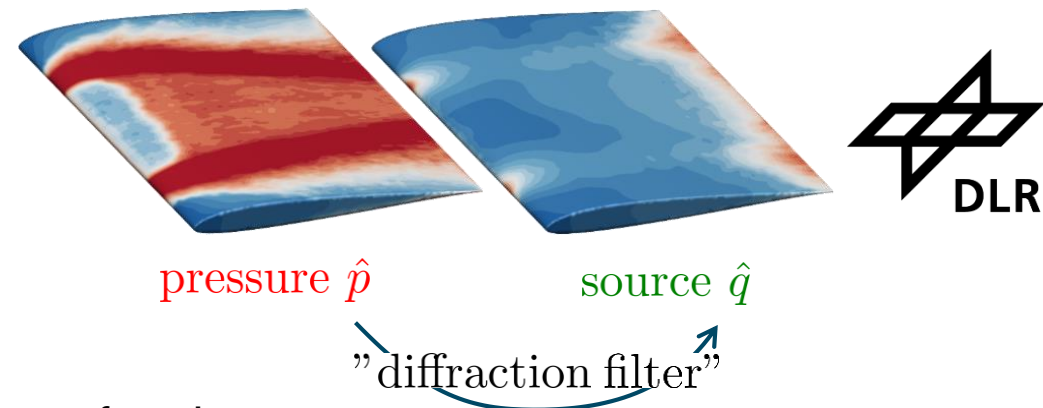
BTGNX experiment



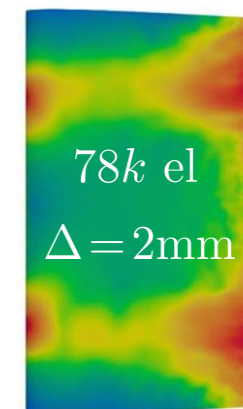
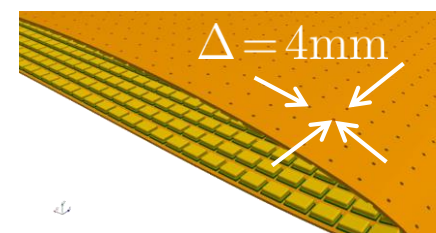
SRS simulation → localization $f(\text{He}_t = 1) \simeq 18\text{kHz}$



Conclusions on source localization

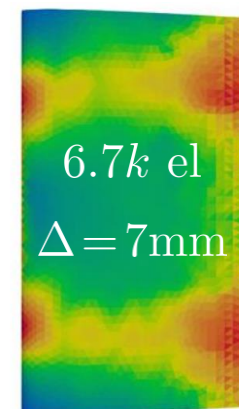


- surface source quantity \hat{q} enables source identification w/o beamforming
- localization first principles based on the hypothesis, that reflection does not generate sound
- source quantity \hat{q}
 - super resolution
 - objective (not depending on observer, nor acoustic installation)
 - natural basis for aeroacoustic cost function (optimisation)
- given flush surface mounted **MEMS** technology \hat{q} could be determined experimentally



800Hz

\hat{p}_S



Summary & Conclusions



- **demonstrated that aircraft noise may be reduced at the source**
 - **know**, what to **do** (1st set of dominant sources successfully treated by „1st gen“ NRTs)
- **any further improvement? → yes!**
 - 2nd set of dominant sources identified, successfully treated by „1st gen“ NRTs
 - Next: go from „1st gen“ to optimum (2nd gen) NRTs
 - aero-shaping (in sense of MDO)
 - materials (best placing, inverse design of meta materials, adaptive/switchable)
 - active (steady flow control, ultimately unsteady source control ← MEMS-sensors/actuators+num. simulation+AI)
- **How?**
 - Exploit today's (num./exp.) capabilities to generate relevant detailed/high quality data
 - Make sense out of data; use **relevant source quantities**, physical + correlation based models with ordinary brains and AI-brains.
- aeroacoustic problems in a/c and ventilation fans very similar
 - **learn from each other (→ meet on conferences like this)**

Thank you !

